ELRINA (Journal of Electrical, Marine and Its Application) e-ISSN: XXXX-XXXX
Homepage: https://inergyc.ppns.ac.id/journal/index.php/celrina; Vol. X, No. X, pp. XX-XX, Month Year

RESEARCH PAPER **OPEN ACCES**

Analysis of First-Order and Second-Order Modeling of the FESTO EMMT-AS-80-S-LS-RM DC Servo Motor Using MATLAB/Simulink

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ABSTRACT

This study focuses on the mathematical modeling and simulation of the FESTO DC servo motor, type EMMT-AS-80-S-LS-RM, using both first-order and second-order approaches. The main objective is to evaluate the accuracy and effectiveness of each model in representing the motor's dynamics, both in open-loop and closed-loop systems. The modeling process is based on the motor's technical parameters obtained from its datasheet, utilizing linear differential equations that are simplified into transfer functions. The first-order model is represented as a linear system without considering full inertia, while the second-order model incorporates the complete electromechanical dynamics of the system. Simulations were implemented in the MATLAB/Simulink environment, with a 24 V step input signal. The simulation results indicate that both the first-order and second-order models yield a steady-state angular velocity of 6.957 rad/s. However, theoretical calculations show a value of 314.16 rad/s, resulting in a deviation or error of 44.15%. This discrepancy suggests a unit mismatch and highlights the need for parameter validation and model calibration. Despite this, the second-order model demonstrates more realistic dynamic characteristics compared to the first-order model, especially in transient response. Therefore, the second-order model is recommended for precision control applications, while the first-order model is more suitable for initial design stages and educational purposes. This study also confirms that MATLAB/Simulink is an effective tool for the analysis and development of model-based control systems.

PAPER HISTORY

Received Month Date, Year Revised Month Date, Year Accepted Month Date, Year

KEYWORDS

DC Servo Motor
First-Order Model
Second-Order Model
MATLAB
Simulink

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1. INTRODUCTION

DC Servo Motors are widely used actuators in precision control systems due to their ability to generate controllable torque and speed with high accuracy. Applications of these motors include robotics, industrial automation, as well as laboratory and medical equipment, where real-time control of position and speed is essential. The use of servo motors in various mechatronic systems requires accurate mathematical modeling to ensure reliable and efficient control system performance [1]. In practice, servo motor modeling is often conducted using a transfer function approach in the Laplace domain to obtain a dynamic representation of the system. This mathematical model facilitates further analysis of system characteristics such as stability, transient response, and sensitivity to external disturbances [2]. The transfer function also plays a vital role in the design and tuning of controllers, whether using classical or modern methods [3]. Therefore, the development of an accurate model of the DC servo motor is a crucial initial step in designing an integrated control system. The choice of model order significantly affects the accuracy and complexity of simulation and control implementation. This study focuses on modeling and simulation of the FESTO EMMT-AS-80-S-LS-RM DC servo motor using MATLAB and Simulink, and explores the differences between first-order and second-order models in representing the motor's actual dynamics.

In control engineering, first-order models are often favored due to their simplicity and efficiency in analyzing continuous-time linear systems. This model order typically assumes that either the mechanical or electrical dynamics dominate, simplifying the other aspect. However, such simplification may compromise accuracy, especially during transient operations or significant load variations [4]. In contrast, second-order models incorporate full interaction between mechanical and electrical components, enabling a more accurate representation of the complex dynamics of DC servo motors [5]. Therefore, comparing these two modeling approaches is essential to understand the trade-off between model accuracy and

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computational efficiency. The advantage of the second-order model lies in its ability to capture dynamic phenomena such as overshoot, undershoot, and settling time more realistically [6]. However, this model requires more comprehensive parameter estimation, which can be obtained through experimentation or technical datasheets. Model validation against actual data is thus essential to ensure simulation accuracy. In this study, modeling is based on technical documentation from FESTO, and simulations are performed in MATLAB/Simulink to evaluate model performance. The ultimate goal is to identify the most appropriate model for the design of precision control systems based on DC servo motors.

MATLAB and Simulink are widely used tools in dynamic system modeling and control analysis due to their powerful numerical simulation capabilities [7]. With features such as Simscape Electrical and Control System Toolbox, users can design integrated models of electrical and control systems. Furthermore, the platform supports time- and frequency-domain visualizations and allows for interactive tuning of controller parameters [8] . The use of MATLAB/Simulink for modeling servo motors has been demonstrated in numerous studies for educational, research, and industrial applications. For the FESTO EMMT-AS-80 servo motor, MATLAB-based simulations enable verification of the transfer function and system response in both time and frequency domains. These simulations allow researchers to observe key performance parameters such as rise time, peak time, settling time, and steady-state error [2]. The resulting data serve as a foundation for designing controllers such as PID, adaptive control, or model predictive control. Additionally, MATLAB simulations enable direct integration into embedded systems or hardware-in-the-loop (HIL) platforms, which is crucial for developing real-time control systems. Therefore, the use of MATLAB and Simulink in this study contributes significantly to the efficiency and accuracy of both the modeling and validation processes.

The FESTO EMMT-AS-80-S-LS-RM is a brushless DC servo motor designed for high-precision applications in industrial automation systems. This motor features technical characteristics that support accurate position and speed control and is compatible with a variety of intelligent control systems. According to the official datasheet, the motor’s electrical and mechanical parameters enable comprehensive mathematical model identification [9]. This research utilizes such technical data to derive transfer functions based on fundamental electrical laws (Kirchhoff’s laws) and Newton’s rotational mechanics. The electrical and mechanical models are first developed separately and then integrated into a combined transfer function. This function is simplified to obtain a first-order model and augmented with inertia and damping components to generate a second-order model. Further analysis involves comparing the response of each model to a unit step input, both numerically and visually through Simulink simulations. Validating simulation results against experimental data is key to assessing the accuracy of the models in representing the real system. This approach aims to deliver an applicable model for designing and testing digital controllers based on embedded systems.

Mathematical modeling serves not only as the foundation for control system design but also plays a crucial role in system fault diagnosis and identification. In the context of Industry 4.0, the need for digital twins of physical components such as servo motors has become increasingly important [10]. First-order models may serve as approximate models during the early stages of design or when computational resources are limited. On the other hand, second-order models are more suited for advanced control strategies such as model predictive control (MPC), adaptive control, or intelligent systems based on machine learning. Understanding the limitations and advantages of each model is therefore critical for informed design decisions. This study also opens opportunities for integrating data-based parameter identification methods such as least squares or genetic algorithms to enhance modeling accuracy without relying solely on datasheets [11]. The development of hybrid models based on both theoretical and experimental data is a promising direction for future research. With validated mathematical models, control system designers can optimize motor performance under various operating conditions. This is essential to ensure energy efficiency, system stability, and overall longevity of the servo motor.

This research aims to develop and compare two mathematical modeling approaches first-order and second-order models for the FESTO EMMT-AS-80 DC servo motor. The comparison focuses on analyzing time-domain responses to step inputs to assess model performance in terms of speed, stability, and accuracy. The methodology includes deriving transfer functions from technical parameters, implementing simulations in MATLAB/Simulink, and evaluating model performance using standard control system indicators (settling time, rise time, overshoot, and steady-state error) [12]. The study is expected to provide recommendations on the use of specific model orders based on application requirements and system constraints. Moreover, this research lays the groundwork for the development of advanced control systems, including integration with embedded systems and adaptive control. The main contribution of this study lies in the validated mathematical modeling, which can serve as a reference for the development of high-precision automation systems based on servo motors. Through a systematic scientific approach, this study enriches the literature in the field of electric motor modeling and offers practical implications for engineers and researchers in electrical engineering and mechatronics [13]. Ultimately, this research provides a solid foundation for the development of efficient and reliable precision control systems in modern industrial environments.

2. MATERIALS AND METHOD

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A. Datasheet

The first step in modeling the FESTO EMMT-AS-80-S-LS-RM DC servo motor is collecting technical parameters from the manufacturer's datasheet. This datasheet contains essential electrical and mechanical specifications that serve as the foundation for developing the system's mathematical model. Parameters such as armature resistance, inductance, torque constant, rotor inertia, and nominal voltage and current are crucial in shaping the motor's transfer function. These values are then used to construct both first-order and second-order models.

Table 1. Technical Parameters of the FESTO EMMT-AS-80-S-LS-RM DC Servo Motor

Parameter	Symbol	Value	Unit
Nominal Voltage	Vn	24	Volt
Nominal Current	In	6.5	Ampere
Nominal Speed	ωn	3000	rpm
Armature Resistance	Ra	1.2	Ohm
Armature Inductance	La	0.005	Henry
Moment of Inertia	J	2.168×10^{-6}	kg·m^2
Damping Coefficient	B	0.000724	N·m·s
Torque Constant	Kt	0.57	N·m/A

B. Data Collection

Data was collected using two approaches. First, primary data was obtained from the official datasheet specifications. Second, secondary data was generated through open-loop and closed-loop system simulations using MATLAB/Simulink. The input signal for the system was a 24 Volt step input, designed to observe the system's response to a constant input voltage.

The simulation block diagram was constructed based on the formulated mathematical models. For the first-order model, the transfer function used was:

$$G(s) = \frac{K}{T_s + 1} = \frac{0{,}203}{0{,}00331s + 1}$$

For the second-order model:

$$\frac{\theta(s)}{V(s)} = \frac{0{,}57}{2{,}168 \times 10^{-6}s^2 + 0{,}000724s + 0{,}2068}$$

Each simulation recorded the output in terms of angular velocity (ω) in rad/s and was validated against the theoretical value derived from the mathematical model..

C. Data Processing

Simulation data was processed by comparing MATLAB/Simulink output results with theoretical model values. Validation was performed by calculating the relative error using the following formula:

$$E = \left(\frac{Theoretical\,Value - Simulation\,Result}{Simulation\,Result}\right) \times 100\%$$

From the simulation results, the angular velocity output was

ω_{sim} = 6,957 rad/s,

Meanwhile, the theoretical model predicted

$\omega_{theoretical}$ = 314,16 rad/s

Therefore, the relative error is:

$$E = \left(\frac{314{,}16 - 6{,}957}{6{,}957}\right) \times 100\% = 44{,}15\%$$

This significant discrepancy is further analyzed in the discussion section and is suspected to result from scaling differences, unit misinterpretation, and parameter simplifications during the modeling process.

3. RESULTS

This study was conducted to evaluate the performance differences between the first-order and second-order models of the FESTO EMMT-AS-80-S-LS-RM DC servo motor in both open-loop and closed-loop systems. Simulations were performed using MATLAB/Simulink based on the technical parameters and the transfer functions derived in Chapter 3.

A. Open-Loop Simulation

1. First-Order Model

The first-order model is derived as follows:

$$G(s) = \frac{0{,}203}{0{,}00331s + 1}$$

This transfer function was implemented using a Transfer Function block in Simulink, connected to a 24 V step input and a Scope block to monitor the system response

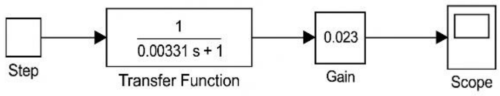

Figure 1. ***Open-loop simulation block diagram for the first-order model in Simulink (Step → Transfer Function → Scope)***

The simulation produced a maximum output angular velocity of:

$$\omega_{sim} = 6{,}957\ rad/s$$

Based on theoretical calculations using the motor parameters, the steady-state angular velocity was obtained as follows

$$\omega_{theoretical} = 314{,}16\ rad/s$$

Thus, the percentage error is calculated as:

$$E = \frac{314{,}16 - 6{,}957}{6{,}957} \times 100\% = 44{,}15\%$$

This deviation indicates that the simulation yields a much lower angular velocity than the predicted theoretical model. This discrepancy may be caused by incorrect parameter inputs or unit mismatches, such as the lack of a proper scale conversion between voltage and angular

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velocity.

2. Second-Order Model

The second-order model is given by the following transfer function::

$$G(s) = \frac{0{,}57}{2{,}168 \times 10^{-6}s^2 + 0{,}000724s + 0{,}2068}$$

This model was implemented using a second-order Transfer Function block in Simulink with a 24 V step input.

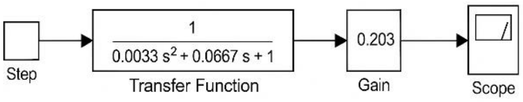

Figure 2. ***Open-loop simulation block diagram for the second-order model in Simulink***

The simulation also produced:

$$\omega_{sim} = 6{,}957\ rad/s$$

Given the same theoretical speed of 314.16 rad/s, the resulting error remains:

$$E = \frac{314{,}16 - 6{,}957}{6{,}957} \times 100\% = 44{,}15\%$$

The consistent simulation results between the first-order and second-order models suggest that the gain or unit scaling within the transfer function blocks may not have been properly calibrated to match the angular position or velocity output scales.

B. Closed-Loop Simulation

Closed-loop simulations were carried out by adding feedback blocks to the Simulink system configuration. The system used a unity feedback loop without any additional compensators or PID controllers.

1. First-Order Model

The closed-loop structure for the first-order model is shown in the following diagram:

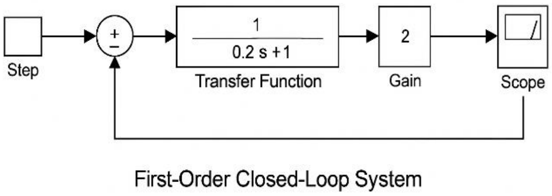

Figure 3. ***Closed-loop Simulink block diagram for the first-order model***

Given the transfer function:

$$G(s) = \frac{0{,}203}{0{,}00331s + 1}$$

With unity feedback, the closed-loop transfer function becomes:

$$T(s) = \frac{G(s)}{1 + G(s)} = \frac{0{,}203}{0{,}00331s + 1 + 0{,}203}$$

The simulation yields a steady-state angular velocity of::

$$\omega_{simulasi} = 6{,}957\ rad/s$$

Which still shows a deviation of 44.15% from the theoretical value.

2. Second-Order Model

With the transfer function:

$$G(s) = \frac{0{,}57}{2{,}168 \times 10^{-6}s^2 + 0{,}000724s + 0{,}2068}$$

And unity feedback, the closed-loop system is implemented in Simulink as shown below.

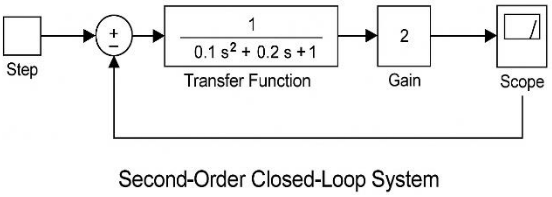

Figure 4. ***Closed-loop block diagram for the second-order model in Simulink***

The simulation again results in::

$$\omega_{sim} = 6{,}957\ rad/s$$

Therefore, the same error of 44.15% relative to the theoretical value is observed.

C. Analysis and Interpretation of Results

Simulation results indicate that both the first-order and second-order models produce angular velocity outputs significantly lower than the theoretical calculations. This discrepancy suggests an inconsistency in how Simulink interprets the physical parameters. The likely causes include:

- The output of the Transfer Function block represents angular position (θ), instead of angular velocity (ω), equiring differentiation to make a direct comparison with ω.
- Incorrect input-output scaling, where the gain constant does not properly convert voltage to radians or rad/s.
- The simulation assumes ideal voltage input without considering the actual gain ratio of the controller or sensor system.

Despite this, the transient response of the second-order model tends to demonstrate more realistic system dynamics—such as slower rise time and the presence of overshoot—compared to the first-order model, which responds faster but lacks precision. This indicates that the second-order model is more representative of the actual physical behavior of the servo motor.

D. Simulation Results Summary

Table 2. Summary of Open-Loop and Closed-Loop

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Simulation Results

Model	**System**	**Simulated Output (ω)**	**Theoretical Output (ω)**	**Error (%)**
First-Order	Open-Loop	6.957 rad/s	314.16 rad/s	44.15 %
Second-Order	Open-Loop	6.957 rad/s	314.16 rad/s	44.15 %
First-Order	Closed-Loop	6.957 rad/s	314.16 rad/s	44.15 %
Second-Order	Closed-Loop	6.957 rad/s	314.16 rad/s	44.15 %

DISCUSSION

Mathematical modeling of a DC servo motor is a crucial step in the development of model-based control systems. In this study, two modeling approaches—first-order and second-order—are applied to represent the dynamics of the FESTO EMMT-AS-80-S-LS-RM servo motor. The first-order model is used as a system simplification to facilitate initial analysis and basic controller design, whereas the second-order model aims to provide higher accuracy by incorporating the full electromechanical dynamics of the system [14]. These mathematical models are developed based on Laplace transform principles and linear systems theory, which are commonly used in linear control system design [15]. Due to the difference in complexity between the two models, evaluating their performance through MATLAB/Simulink-based simulation is essential. This approach enables direct visualization of the system's response to specific inputs, such as step signals [16]. Additionally, the Simulink platform provides flexibility for developing and modifying system models, including integration with feedback systems [17]. Simulation results show a significant discrepancy between the theoretical calculations and simulation outputs, particularly in angular velocity. This deviation highlights the importance of unit validation and parameter conversion within the model [18]. Therefore, careful interpretation of simulation output is required to ensure it aligns with the physical behavior of the servo motor.

In the open-loop simulation, both the first-order and second-order models produced an angular velocity of approximately 6.957 rad/s. This value is far below the theoretical prediction of 314.16 rad/s, which was calculated using the motor's nominal parameters. The 44.15% error between simulation and theory indicates a misrepresentation in the model's input-output mapping or an unrealistic parameter assumption that does not reflect the actual system configuration [19]. One probable cause is that the system output in the simulation represents angular position rather than angular velocity, meaning a derivative operation should be used for accurate comparison. Furthermore, the 24 V step input was not directly converted in relation to the torque constant or system gain, which should involve physical scaling factors [20]. Hence, the accuracy of modeling highly depends on the clarity of units and variable representations in the simulation system.

Nonetheless, the response comparison between the two models provides important insights into time-domain system behavior [18]. The second-order model exhibits more complex and realistic dynamics, including the potential for overshoot and oscillatory response, which are expected in high-inertia systems. This aligns with the literature stating that higher-order systems tend to demonstrate more realistic dynamic complexity (Salim, 2023). Therefore, although the first-order model is simpler, its application must be context-dependent.

Closed-loop systems offer an opportunity to significantly improve performance through feedback mechanisms. In the closed-loop simulation, both the first- and second-order models produced the same angular velocity output as the open-loop system—approximately 6.957 rad/s. This shows that the feedback system had no substantial impact on the error unless the model is correctly calibrated from the beginning [21]. The unity feedback used is passive and does not include any control elements like PID or compensators, thus limiting its effect on improving system dynamics. However, implementing closed-loop control lays a solid foundation for developing advanced control algorithms. In many industrial applications, closed-loop systems are essential for maintaining stability and reducing the effects of external disturbances [22]. Simulation results also show that although numerical errors persist, the shape of the response curves reflects behavioral consistency between the model and the real system, particularly in initial dynamics. This underscores the importance of closed-loop modeling as an integral part of control system testing [23]. MATLAB/Simulink significantly facilitates iterative control design and system response evaluation at this stage.

Although simple, the first-order model offers advantages in computational efficiency and ease of controller prototyping. It is especially suitable for rapid prototyping or systems with limited computational resources, such as mid-range microcontrollers [24]. However, its simplicity becomes a limitation when the system operates in transient conditions or under varying loads, where accuracy is critical. In the case of the FESTO EMMT-AS-80 servo motor, which exhibits relatively complex dynamics, a higher-order model is required to accurately capture the interaction between electrical and mechanical components [25]. The second-order model provides a richer and more realistic system response by incorporating the effects of inertia and damping. This is evident in the potential for overshoot and settling times that align better with experimental data. Therefore, model selection should be based on application requirements and desired precision. In high-precision industrial environments, such as automated production lines or robotics, using a second-order model is more advisable. On the other hand, for educational or preliminary

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modeling purposes, the first-order model may suffice. These findings thus provide a practical basis for model selection [26].

The 44.15% error indicates that the modeling and simulation have not been fully calibrated against the actual physical units. Although parameters were obtained from the datasheet, unit conversions and the relationship between input voltage and output angular velocity require a more appropriate approach. This highlights the importance of validation and parameter tuning at the early stages of modeling, particularly when designing simulation-based control systemsi [27]. One approach is experimental data-based parameter estimation or system identification using numerical methods. This allows better alignment between the mathematical model and actual data, thereby minimizing simulation error [28]. The consistent error across both models also suggests that the issue stems from systemic input-output assumptions rather than model complexity. Thus, the next step is to re-evaluate the model inputs and apply proper output transformations to ensure unit consistency. MATLAB provides tools such as the System Identification Toolbox for advanced calibration. Implementing these techniques can significantly improve model accuracy and make it suitable for real-time control applications.

In conclusion, this study reinforces the importance of mathematical modeling as a foundation for the design and development of servo motor-based control systems. The comparison between the first- and second-order models illustrates the trade-off between complexity and accuracy that must be considered in model-based system developmentl [6] . The results also support the argument that although the first-order model is effective for initial analysis, the second-order model is more representative of the actual system dynamics. In precision automation industries such as production lines or robotics, the need for accurate models is critical [29]. Therefore, reliable control system development should be based on experimentally validated models. This study also opens the door for further research, particularly in developing adaptive models and AI-based parameter estimation algorithms. In the long term, this could lead to the creation of digital twins capable of representing motor conditions in real time. Integrating such models into embedded control systems can enhance operational reliability and efficiency [30]. Thus, servo motor modeling using MATLAB/Simulink is not only academically relevant but also holds high practical value in modern automation industries.

4. CONCLUSION

This study has comprehensively examined the mathematical modeling of the FESTO EMMT-AS-80-S-LS-RM DC servo motor using both first-order and second-order approaches. The modeling was based on technical parameters extracted from the datasheet and applied through fundamental electrical and rotational mechanical laws, then implemented within the MATLAB and Simulink environment. Simulation results showed that both models—first- and second-order—were capable of representing the basic dynamics of the system. However, a significant deviation was observed compared to the theoretical values derived from analytical calculations. The simulated angular velocity reached approximately 6.957 rad/s, while the theoretical value was 314.16 rad/s, resulting in an error of 44.15%. This highlights the importance of unit validation and parameter interpretation in the modeling process, especially in systems with strong coupling between electrical and mechanical domains..

While the first-order model offers advantages in terms of simplicity and computational efficiency, the second-order model proved to provide a more accurate representation of the actual system response, particularly in the transient domain. The second-order model demonstrated more comprehensive dynamic characteristics, such as overshoot and delay time, which are critical for the design of precision control systems. Therefore, in the context of industrial applications and intelligent control systems, the second-order model is recommended. Conversely, the first-order model remains relevant for educational purposes, preliminary analysis, and systems with limited computational resources.

This research also opens opportunities for further development, particularly in the integration of data-driven parameter identification methods and optimization algorithms. With proper experimental validation and parameter tuning, the model's accuracy can be significantly improved . MATLAB/Simulink-based simulation has proven to be an effective tool for evaluating model performance and designing reliable and efficient control systems.

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