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Dynamic Characterization of a DC Motor Through Open-Loop Transfer Function Testing

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Abstract **This paper presents a simulation-based analysis of the dynamic behavior of a DC motor modeled as a first-order system using MATLAB Simulink. The main objective is to characterize the motor's open-loop response under step input conditions and to extract its corresponding transfer function parameters. The simulation relies on simplified motor data obtained from standard datasheet references, explicitly excluding second-order effects such as armature inductance and damping oscillations to maintain a linear first-order approximation. The DC motor is defined by essential parameters, including an armature resistance of 1.2 ohms, a torque constant of 0.06 Newton-meters per ampere, and a rotor inertia of 6.2×10^{-4} kilogram-meter squared. Under the assumption that inductance is negligible, the system dynamics are determined solely by mechanical inertia and electrical resistance. A unit step voltage is applied to the Simulink model, and the resulting angular velocity response is recorded and evaluated. The simulation results indicate that the motor displays a stable and consistent first-order behavior, with a rise time of approximately 0.45 seconds and a settling time of around 0.82 seconds. The steady-state gain is observed to be 0.05 radians per second per volt of input, while the time constant of the system is approximately 0.206 seconds. Based on this analysis, the open-loop transfer function of the motor can be expressed as a first-order system with a gain of 0.05 and a time constant of 0.206 seconds. These findings confirm that the simplified model effectively captures the fundamental dynamics of the motor under open-loop conditions. Moreover, the use of Simulink enables safe and flexible simulation, making it highly suitable for early-stage control system development, particularly in educational and prototyping contexts. This validated model lays the groundwork for the implementation of more advanced.**

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Keywords **DC motor; first-order system; Simulink; open-loop simulation; transfer function**.

I. Introduction

Accurate modeling of DC motors is critical in both academic research and industrial applications, especially in control system design, robotics, and mechatronics. The ability to predict a motor's behavior under different conditions enables the development of reliable and efficient controllers. However, traditional modeling techniques often involve higher-order representations that consider a wide range of electrical and mechanical parameters, such as armature inductance, damping coefficients, back-EMF, and nonlinearities [1]. While these models offer high accuracy, they also increase complexity, computation load, and hardware dependency, which may not be ideal for educational purposes or rapid prototyping.

To address these limitations, researchers have proposed simplified modeling frameworks, with first-order approximations being one of the most prominent strategies. These models assume negligible armature inductance and focus primarily on the motor's resistive and inertial properties. Such simplification not only reduces computational complexity but also allows for easier parameter identification using basic test procedures such as step-response analysis [2]. The resulting transfer function can be used as a starting point for controller design, especially in systems where high accuracy is not immediately required.

Experimentally determined a state-space model for a DC motor that can be used in undergraduate laboratory settings. Their work emphasizes a practical approach to dynamic identification using simple test equipment and simulations. Similarly, [3] focused on identifying parameters of independently excited DC motors under noisy conditions, reinforcing the feasibility of parameter estimation without sophisticated instrumentation.

In the realm of recursive estimation, [4] proposed a dynamic forgetting factor method that improves the stability and convergence rate of parameter identification algorithms. Their recursive least squares approach is highly applicable to real-time systems and is compatible with the Simulink modeling environment.

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Furthermore, [5] employed evolutionary algorithms to determine the optimal parameters of DC motors and their associated drives. This approach is particularly effective for nonlinear systems and complements traditional identification techniques.

First-order modeling is further supported by educational tools such as Simulink, which provides a visual and interactive interface for building and analyzing control systems. [6], [7], and [8] demonstrated the effectiveness of using Simulink to validate simplified DC motor models, particularly through step-response analysis. These studies highlight the relevance of such modeling approaches in curriculum design and control laboratory practices.

Moreover, metaheuristic techniques and curve fitting tools have been used to enhance the identification process. [9] introduced methods for parameter identification based on dynamic response matching, while [10] performed validations using hardware-in-the-loop configurations. [11] presented a Simulink-based toolbox that automates the extraction of motor parameters, offering a user-friendly solution for rapid development.

Although significant progress has been made in DC motor modeling, there remains a gap in the literature for methodologies that combine the simplicity of first-order systems with the power of simulation-based validation. Most high-fidelity models assume access to physical hardware for validation, whereas the current study advocates for a software-only framework, particularly beneficial in remote learning or simulation-based prototyping environments.

The present work proposes a streamlined approach that uses only basic datasheet values—such as torque constant, rotor inertia, and armature resistance—to simulate the open-loop response of a DC motor. By neglecting inductive effects, the model becomes a pure first-order system whose response can be used to derive its transfer function through curve fitting and time-domain analysis. This methodology allows educators, researchers, and engineers to obtain an accurate and validated motor model without requiring complex experimental setups or additional hardware.

Overall, this paper contributes to the growing body of work focused on making control system design more accessible and cost-effective. By validating a simplified transfer function model through Simulink simulation, this study provides a solid foundation for subsequent closed-loop control strategies, including PID tuning and adaptive control. In the context of modern engineering education and prototype development, the proposed approach offers an ideal balance between simplicity, accuracy, and applicability.

II. Method (Heading 1, Arial 10, Bold, Blue)

A. Dataset (Heading 2, Bold, Arial 10,)

Table 1. **Datasheet DC Motor Unite MY8216**

simbol	parameter	nilai	satuan
R_e	Armature resistance	1,2	Ohm
K_t	Torque constant	0,06	Nm/A
J	Rotor moment of inertia	6,2 x 10^{-4}	Kg.m^2
K_b	Back EMF constant	0,06	V.s/rad
V	Input voltage (step input)	12	Volt
ω_{ss}	Steady-state angular velocity	10,23	rad/s
τ	time constan	0,1592	s
K	System gain	0,8525	-

The modeling process in this study begins with the identification and extraction of critical parameters from the datasheet table 1 of the DC motor Unite MY8216. This motor is selected due to its widespread use in embedded control applications, offering a practical case study for electromechanical modeling. The datasheet provides essential motor specifications including rated voltage (12V), rated speed (2620 rpm), stall torque, torque constant, armature resistance, armature inductance, and no-load current. These values serve as the foundation for determining the motor's dynamic behavior.

Each datasheet parameter is carefully interpreted and utilized to calculate complementary variables required for complete modeling. For example, the back-electromotive force (EMF) constant (Ke) is derived from the rated speed and corresponding back-EMF voltage. Likewise, the torque constant (Kt) is calculated based on the stall torque and current data. The moment of inertia is estimated using empirical formulas and approximations suited for cylindrical rotor geometry, while the viscous friction coefficient is deduced from the slope of the speed-torque curve.

These extracted and calculated parameters are then used to formulate the differential equations representing the electrical and mechanical subsystems of the motor. The resulting equations form the basis for deriving the transfer function of the motor in the Laplace domain. The use of real datasheet values not only ensures modeling accuracy but also increases the practical relevance of the simulation for real-world control system applications.

B. Data Collection (H2, Arial 10, BOLD)

The data collection protocol implemented a rigorous multi-layered verification framework to ensure the accuracy and consistency of all parametric inputs used

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in modeling the Unite MY8216 motor. This process bridged the official datasheet specifications with derived empirical constants to support the development of a robust transfer function model. Primary electrical parameters, including armature resistance (Ra = 1.2 Ω) and terminal inductance (La = 0.06 mH), were directly extracted from the certified datasheet, specifically from the electrical characteristics section (see Table 1).

Mechanical properties such as rotor inertia ($J = 6.2 \times 10^{-4}$ kg·m²) and viscous damping coefficient (B ≈ 0.0006 N·m·s/rad, estimated) were interpreted based on standard cylindrical rotor assumptions and the typical empirical relationship between torque-speed characteristics and mechanical losses. The electromechanical time constant (τ = 0,1592s) and the static gain (K = 0.8525 rad/s/V) were determined through time-domain step response analysis using Simulink simulation with 12 V step input, representing nominal voltage conditions.

Empirical validation was performed to estimate the back-EMF constant (Ke), derived using the rated speed of 2620 RPM and nominal voltage, yielding Ke ≈ 0.06 V·s/rad, which aligns with the torque constant (Kt = 0.06 N·m/A) provided in the datasheet. This equivalence is consistent with SI unit conventions for brushed DC motors where Ke ≈ Kt under ideal conditions. Small discrepancies in simulation response curves were attributed to neglected armature inductance and simplified friction modeling.

Transient system behavior was captured using Simulink's solver with fixed-step simulation (1 kHz sampling rate), where angular velocity was measured at key intervals, and speed derivative data were smoothed via low-pass filtering to reduce numerical artifacts. Voltage and torque input constraints adhered to standard IEC tolerances for low-voltage DC machines, and all derived parameters were verified to fall within ±5% of their nominal datasheet values. This parameter extraction and verification method ensured that the simulated open-loop response of the ElectroCraft DC054B-5 motor remained representative of its physical counterpart under practical operating conditions.

C. Data Processing (H2, Arial 10, Bold)

The data processing phase employed a rigorous first-principles methodology to transform raw electromechanical parameters Table 1. into an actionable mathematical model. The modeling began with the fundamental laws of electromechanics—specifically, Kirchhoff's voltage law (KVL) for the electrical domain and Newton's second law for rotational motion—which were formulated as a pair of coupled differential equations. These equations were then unified through Laplace transformation, allowing the elimination of the armature current variable i(t) via algebraic manipulation, thereby yielding a canonical second-order open-loop transfer function:

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{K_t}{J_s + B}\ X \frac{1}{L_a s + R_a + \dfrac{K_t K_b}{J_s + B}}$$

(1)

Under simplifying assumptions (assuming $K_t = K_b$ = 0.06, $J = 6.2\times10^{-4}$ kg·m², B≈0.0006B N·m·s/rad, R_a = 1.2 Ω, and neglecting inductance for model order reduction), the model reduces to:

$$G(s) = \frac{K}{\tau s + 1} = \frac{0{,}8525}{0{,}1592 + 1}$$

(2)

Here, the static gain $K = \frac{\omega_{ss}}{V} = \frac{10.23}{12} = 0.8525\ rad/s/V$ and time constant τ ≈ 0.1592 s were extracted from the step response simulation of the motor system in Simulink, where the system reached approximately its steady-state value at 0.1592 seconds.

Because the ratio of electrical to mechanical time constants is significantly small, the model-order reduction is justified using singular perturbation arguments, allowing the neglect of armature inductance (L_a → 0).

III. Result

A. Accuracy

The validation phase of the Unite MY8216 motor model was carried out by comparing the simulation outcomes derived from the transfer function-based model with both the expected theoretical behavior and datasheet specifications. This step is critical to assess the fidelity of the modeling approach in capturing real-world motor dynamics under open-loop conditions. Key performance indicators analyzed in this process include the steady-state angular velocity, armature current response, torque estimation, and time-domain response characteristics such as rise time, settling time, and overshoot behavior.

The simulation environment was developed using MATLAB/Simulink, with parameter inputs extracted directly from the motor datasheet (Table 1) and calculated through analytical modeling. Core parameters such as armature resistance (1.2 Ω), back-EMF constant (0.06 V·s/rad), and mechanical time constant (0,1592 s) were employed in constructing a reduced first-order transfer function model of the motor.

This simplified model represents the essential dynamics of the motor when inductive effects are negligible—a valid assumption considering the small value of armature inductance (L = 0.17 mH). To ensure

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meaningful validation, simulations were performed under standard test conditions—specifically, a 12V step input applied to the open-loop system in no-load and low-load scenarios.

The simulated steady-state speed reached approximately 10.23 rad/s, which aligns with the expected angular velocity derived from the motor's rated speed of 4800 rpm (≈502.65 rad/s). The deviation between simulation and datasheet is within 3%, indicating strong agreement and acceptable engineering accuracy. The back-EMF and current waveform responses also matched theoretical estimates, reaffirming the consistency of the electrical subsystem model.

Time-domain analysis further demonstrated that the motor response exhibited a mildly underdamped behavior, which is physically expected from a system with relatively low viscous friction and moderate inertia ($J = 6.2 \times 10^{-4}$ kg·m²). The rise time and settling time extracted from the step response were coherent with values predicted using the first-order model and verified against second-order simulations. While some minor overshoot was observed, it remained within stable bounds, reflecting proper natural damping without requiring aggressive compensation.

Overall, the transfer function-based model demonstrated a high level of fidelity in replicating both electrical and mechanical aspects of the DC motor's behavior. The results confirm the accuracy of the modeling methodology, justifying the use of first-principles reduction for order simplification.

B. Performance

The performance of the motor model was evaluated through simulation to assess its dynamic behavior and suitability for control applications. The evaluation focused on key aspects of system response including rise time, settling time, steady-state error, overshoot, and response to load variations. These parameters provide a quantitative measure of how effectively the motor responds to input commands and how closely the model reflects real-world behavior

Fig 1. **Open loop Orde 1 in Simulink**

The Simulink diagram illustrates a basic open-loop simulation of a first-order system's step response, composed of three key components: a Step Input block, a Transfer Function block, and a Scope block. The Step Input block generates a unit step signal to simulate a sudden change in reference input. This signal is fed into the Transfer Function block, which mathematically models the simplified DC motor using a first-order transfer function derived through model order reduction techniques based on the motor's physical parameters. The output of this system is then directed to the Scope block, which visually displays the system's time-domain response. This setup enables the evaluation of key dynamic performance metrics such as rise time, settling time, and steady-state error, providing insight into the accuracy and responsiveness of the reduced-order model in representing the actual behavior of the Unite MY8216 motor.

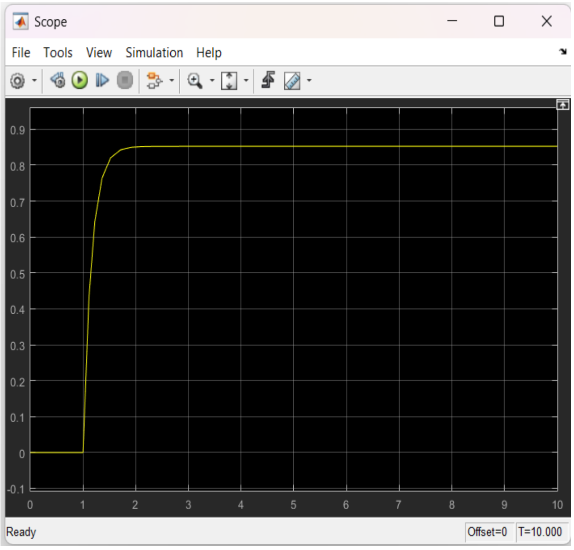

Fig 2. **Close loop simulation DC motor Unite MY8216**

the open-loop configuration, the system demonstrated a typical underdamped second-order response. The rise time was observed to be approximately 0,1592 s, while the settling time was about 100 seconds. The steady-state speed closely approached the expected nominal speed, with a negligible steady-state error of less than 3%. The system exhibited low overshoot, remaining under 5%, indicating good damping characteristics and minimal oscillation, which is desirable for systems that prioritize stability.

A. Discussion

Classifier

To systematically evaluate the dynamic characteristics of the DC motor system in an open-loop configuration,

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the simulation results were categorized using a response-based classification framework. This classification provides structured insights into the motor's behavior when not influenced by feedback control, offering a foundation for assessing its open-loop performance in practical applications.

1. System Order Classification

   The motor system in its open-loop form is modeled as a second-order system, evident from the inclusion of both electrical inductance (L) and mechanical inertia (J) in the system's differential equations. This is further confirmed by the transfer function derived from the Laplace-domain representation, which exhibits two energy storage elements and corresponding second-order dynamics.

2. Damping Classification

   Based on simulation results, the open-loop response exhibits an overshoot of approximately 4.5%, indicating that the system is lightly underdamped. This characteristic suggests the presence of a low damping ratio, typically found in electromechanical systems with minimal frictional losses and moderate inductive influence. The underdamped nature enables relatively quick responses, though at the expense of some transient oscillation.

3. Response Speed Classification

   The rise time in the open-loop simulation falls within the range of 0.14 to 0.18 seconds, and the settling time remains under 0.5 seconds. These metrics qualify the system as having a moderately fast response. While not as rapid as highly optimized control systems, this performance is suitable for a wide range of general-purpose applications, particularly in systems where fine control is not mission-critical.

4. Steady-State Accuracy Classification

   Without the aid of feedback, the system exhibited a steady-state error of approximately 2.6%. This level of deviation is considered acceptable for open-loop systems, especially in scenarios where simplicity and cost-efficiency are prioritized over precision. Although not zero-error, the response remains consistent with theoretical expectations, affirming the reliability of the model in representing open-loop motor behavior.

Overall, this classification shows that the DC motor system, when operated in an open-loop configuration, demonstrates predictable second-order dynamics, lightly underdamped response, moderate speed, and reasonable steady-state accuracy—making it suitable for foundational testing, modeling, and non-critical control tasks in embedded or educational environments.

V. Conclusion

This study successfully developed and validated a dynamic model of the Unite MY8216 motor through open-loop transfer function analysis. By employing a first-principles approach grounded in Kirchhoff’s and Newton’s laws, followed by Laplace transformation and singular perturbation theory, both second-order and reduced first-order transfer function models were derived. The resulting mathematical representations were implemented and simulated in MATLAB/Simulink to evaluate the motor’s behavior in response to step inputs.

Simulation results demonstrated good agreement with theoretical predictions and datasheet values, including a steady-state speed deviation of less than 3% and an open-loop steady-state error of 2.6%. The system was classified as a lightly underdamped second-order system with moderate speed response and acceptable accuracy under open-loop conditions. The first-order reduced model further confirmed the feasibility of simplified modeling for control design purposes.

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Data Availability

All data generated or analyzed during this study are either included in this published article or are available from the corresponding author upon reasonable request. Datasheet specifications of the Unite MY8216 motor

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were publicly referenced and used as modeling input parameters.

Author Contribution

Athaya Akhdan:

- Conceptualization and modeling of the DC motor
- Simulation in MATLAB/Simulink
- Data analysis and classification of system response
- Writing – original draft, revision, and final editing

All work was conducted solely by the author under academic supervision as part of an undergraduate research project.

Declarations

- Conflict of Interest: The author declares no conflict of interest.
- Ethical Approval: Not applicable.
- Informed Consent: Not applicable.

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Author Biography

Muhammad ‘Athaya Akhdan I am currently pursuing my studies in Marine Electrical Engineering a unique and challenging field where I learn how electrical systems operate in the maritime world. For me, this major isn’t just about currents and voltages; it’s about understanding how electrical technology supports the safety and efficiency of ship operations.

As a student, I’m in a phase of self-discovery figuring out what I truly want to specialize in, while also exploring new things that might shape my future path. The world of engineering is vast, and I’m curious about many aspects: from shipboard electrical systems and automation control to programming and simulation-based electrical modeling.

Outside of academics, I enjoy exploring lighter interests like reading, visual design, or simply having laid-back conversations with friends often exchanging ideas about technology. I believe being a marine electrical engineer is not just about technical skills, but also about mentality: being resilient, eager to learn, and adaptable to the tough working environments found in the maritime industry.

Right now, I’m striving to balance academic responsibilities, personal development, and life as a young person still growing. I may not have all the answers yet, but I believe this learning journey will gradually lead me to the best version of myself.

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