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Model Validation and Control of an In-Wheel DC Motor Prototype for Hybrid Electric Vehicles

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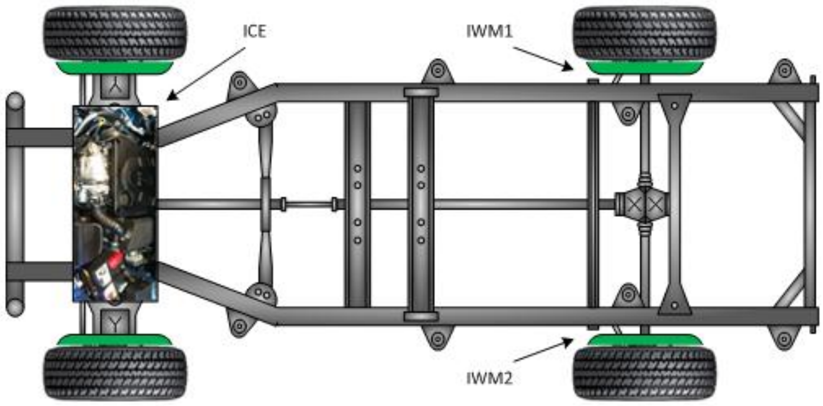
Abstract: In this paper, a mathematical model and a controller for a DC motor are developed for the construction of an in-wheel motor. In-wheel motors can be used in hybrid electric vehicles to provide traction force of front or rear wheels. The model identification is achieved using a simple and low cost data acquisition system. An Arduino Uno embedded board system is used to collect data from sensors to a computer and for control purposes. Data processing is performed using Matlab/Simulink. Validations of the developed mathematical model and controller performance are carried out by comparing simulation and experimental results. The results obtained show that the mathematical model is accurate enough to assist in speed controller design and implementation.

Keywords: DC motor; Model validation; In-wheel motor; Hybrid electric vehicle; Arduino Uno embedded system.

1. Introduction

Since transportation has significant effects on environmental pollution that constitutes a great threat on various life forms on the planet, an efficient vehicular technology is necessary for economic and social evolution. This includes effective technological solutions like utilizing less polluting vehicles with lower fuel consumptions [1]. A hybrid electric vehicle (HEV) represents one of the solutions where it is the culmination of mechanical, electrical, electronic and power engineering technologies. It is a type of vehicle that has two sources of power, namely fuel and a battery [2]. In general, there are several types of HEV such as series and parallel type HEV. In this paper, a through-the-road (TtR) HEV is considered where it consists of an internal combustion engine (ICE) and one or more in wheel-motors (IWMs) to provide traction forces of front and rear wheels respectively. Figure 1 shows the top view of a TtR HEV.

Figure-1. Top view of a TtR HEV [2]



A HEV may utilize IWMs for various reasons such as to increase the energy efficiency and to reduce the weight of the car. The advantages of IWMs include a high torque to weight and volume ratio, low torque ripple, a simple manufacturing process. An IWM is capable of supplying a high torque at low speed for vehicle start up and acceleration. A DC motor possesses these characteristics which makes it an acceptable choice for a gearless application in HEVs [3]. DC motors are extensively utilized in control systems as actuators or control elements in

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process control systems. It is often used to convert an output signal from a controller into torque or an angular displacement to control a process [4].

Several techniques are usually employed for parameter identification of a DC motor. In Saab and Kaed-Bey [5], Saab and Abi Kead-Bey state that system identification methods can be divided into three. The first two approaches are related to closed-loop systems and usually utilized for time-varying systems. The gradient algorithm is a steepest descent algorithm for minimizing the error of identification. In the stochastic state estimation, parameters of the system are estimated by using the Kalman filter and assumed to be unknown states. The third technique, i.e. the least-square method, is applied for linear time invariant systems for minimizing the integral-squared error of the identification. Rahim, *et al.* [6] propose a back-propagation algorithm to train a multilayer perceptron (MLP) network which is used to fit a nonlinear autoregressive moving average with exogenous input (NARMAX) model in Rahim, *et al.* [6]. In Kara and Eker [7], the Hammerstein approach is used for identification of nonlinear systems. It is stated that by implementing the Hammerstein nonlinear model, the problem of nonlinear system identification can be placed in a linear regression form. In addition, many linear system identification approaches can be used to describe efficiently the nonlinearity of a dynamical system. In spite of its simplicity, it can be used to cover a wide area of nonlinear systems. In the same research work, the recursive least square (RLC) method is performed for linear and nonlinear models in online identification. Sendrescu [8] presents a distribution off-line approach algorithm to identify the parameters of a DC motor by using three types of test functions (exponential, sinusoidal and polynomial type) in Sendrescu [8]. The author shows that this algorithm can be used to estimate a continuous-time model from discrete-time data directly. It is reported that the technique is able to provide good results even the in the presence of measurement noise.

Different methods have been introduced to control the speed or position of DC motor since the mid-twentieth century. High efficiency DC motors are essential in any electromechanical systems. In Aydemir, *et al.* [9], carry out a comparison between fuzzy logic controller (FLC) and proportional controller (PI) in controlling the speed of a DC motor for under loaded and unloaded operating conditions. The results show that FLC has a better performance in terms of rise time, steady state error and overshoot, and more sensitive against load disturbance. In Eker [10] discusses the sliding mode control combined with a PID of sliding surface. El-Gammal and El-Samahy [11] introduce the implementation of a particle swarm optimization (PSO) method for tuning the PID speed controller's gain and also show that the efficiency of the optimized PID controller is better than the traditional one by minimizing the values of the steady state error, rise time, overshoot and settling time in El-Gammal and El-Samahy [11]. Murtaza and Bhatti [12] propose sliding mode controller (SMC), integral sliding mode (ISM) controller and dynamic sliding (DSM) controller for controlling a DC motor speed in Murtaza and Bhatti [12]. The researchers report controller robustness and a high control performance even in the presence of external noise and disturbance. The paper claims that the main drawback of SMC (charting) is reduced with the implementations of ISM and DSM methods. In Sharma, *et al.* [13], a technique to control a DC motor through speech recognition using mel-frequency cepstral coefficient (MFCC) to recognize the speech of the user, and vector quantization (VQ) to raise the accuracy of the speech recognition is demonstrated. Morales, *et al.* [14] propose a DC motor control using algebraic derivative estimation, by measuring only angular position and input voltage to the motor in Morales, *et al.* [14]. As reported, the advantages of the method include total independence from the initial conditions of the motor and robustness against the effect of Coulomb friction.

This paper presents the derivation of a DC motor mathematical model based on Newton's and Kirchhoff's laws. The model is constructed using the system identification method. Based on the developed model, a conventional PID and LQR optimal controllers are designed to control the speed of the motor. The model validation and the performance of the controllers are performed in simulation and experimental works. Section 2 describes system identification of a DC motor, after which the controller designs are presented in Section 3. Simulation and experimental results are discussed in Section 4 and the paper is concluded in Section 5.

2. Mathematical Modeling of a Dc Motor

2.1. System Equation

A DC motor is an electromechanical actuator that yields a torque or an angular velocity for a voltage input. Generally, the main objective of DC motor modelling is to relate input voltage to output torque or angular velocity [15]. Figure 2 illustrates a simplified circuitry of a DC motor. The system equation of a DC motor can be derived as follows:

The torque of a DC motor is related to the armature current by

$$T = Ki \tag{1}$$

The electromotive force (emf) voltage is proportional to the angular velocity as given by

$$e_a = K\omega_m = K\frac{d\theta}{dt} \tag{2}$$

From Newton's and Kirchoff's laws we can obtain

$$J\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} = Ki \tag{3}$$

$$L\frac{di}{dt}+Ri=V-K\frac{d\theta}{dt} \tag{4}$$

Applying Laplace transform,

$$Js^2\theta(s)+bs\theta(s)=KI(s) \tag{5}$$

$$LsI(s)+RI(s)=v(s)-Ks\theta(s) \tag{6}$$

The armature current can be expressed as

$$I(s)=\frac{V(s)-Ks\theta(s)}{R+Ls} \tag{7}$$

$$Js^2\theta(s)=Bs\theta(s)=\frac{K(V(s)-Ks\theta(s))}{R+Ls} \tag{8}$$

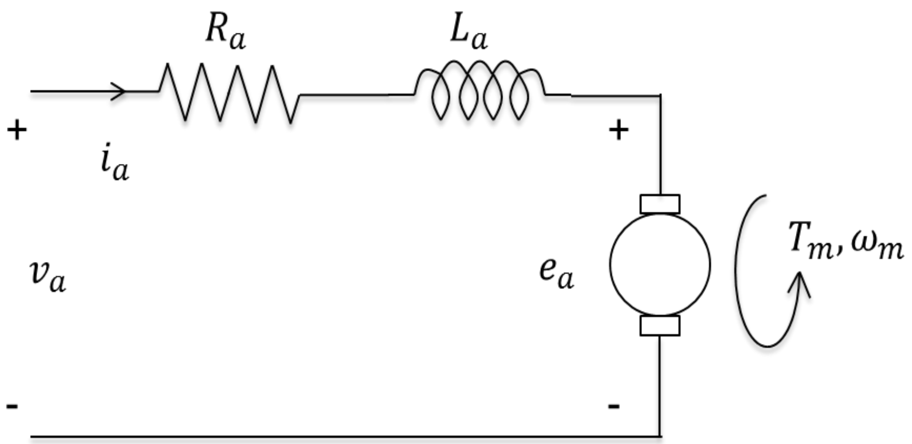
From Eq. (8), a transfer function that relates input voltage to angular position can be written as

$$G_a(s)=\frac{\theta(s)}{V(s)}=\frac{K}{[(R+Ls)(Js+b)+K^2]} \tag{9}$$

Subsequently to angular velocity

$$G_v(s)=\frac{\omega(s)}{V(s)}=\frac{K}{[(R+Ls)(Js+b)+K^2]} \tag{10}$$

Figure-2. A simplified DC motor circuitry



2.2. Experimental Circuit Design

The design comprises of a driver circuit and sensing elements connected to a DC motor to enable data collection and transmission to a computer through a microcontroller. The system consists of an Arduino Uno microcontroller that acts as a data acquisition system, a motor driver as the servo-amplifier and a rotary encoder as a speed sensor. Figure 3 shows the block diagram of the experimental circuit.

Figure-3. Experimental block diagram

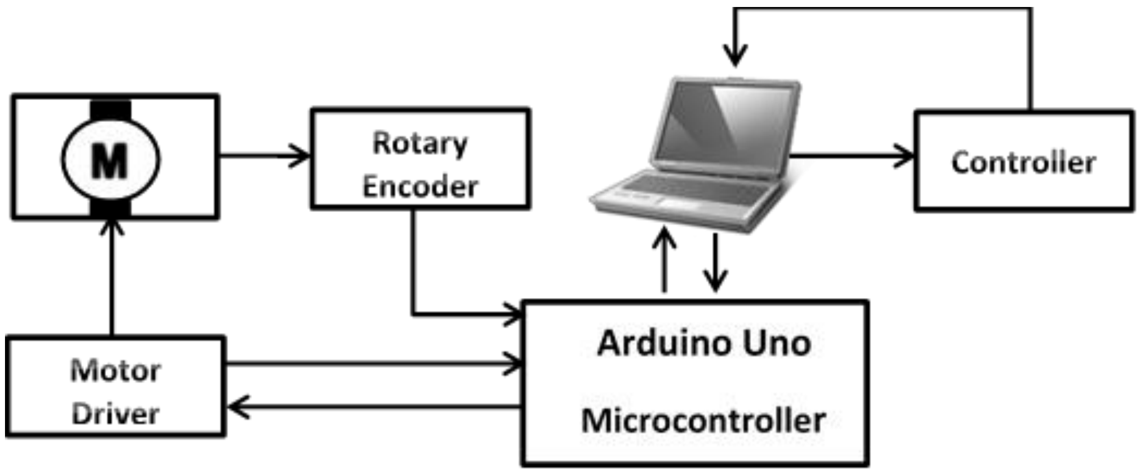


Table-1. DC motor specifications

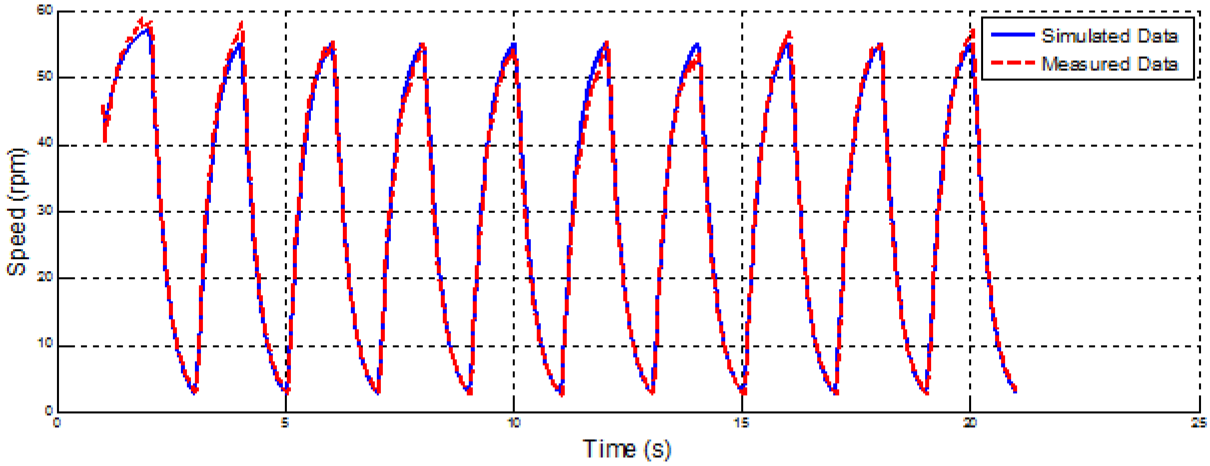
Specification	Value
Operating voltage (V)	12
Output power (W)	3.4
Rated speed (rpm)	170
Rated current (A)	0.9
Rated torque (mN.m)	196

2.3. System Identification

System identification is an important process to describe the behavior of a system of interest through a mathematical model [16]. After which the model validation is applied by comparing the model's output to the measured one to check whether it represent the actual system behavior with acceptable boundaries [17]. The approach involves direct measurements of input and output signals for the purpose of fitting a mathematical model. Using Matlab/Simulink, a best fit of 94% is produced as shown in Figure 4. From the system identification process, a transfer function in the form of Eq. (9) is obtained as follows

$$G_v(s) = \frac{1504}{s^2 + 19.05s + 50.58} \tag{11}$$

Figure-4. System Identification result



3. Controller Design

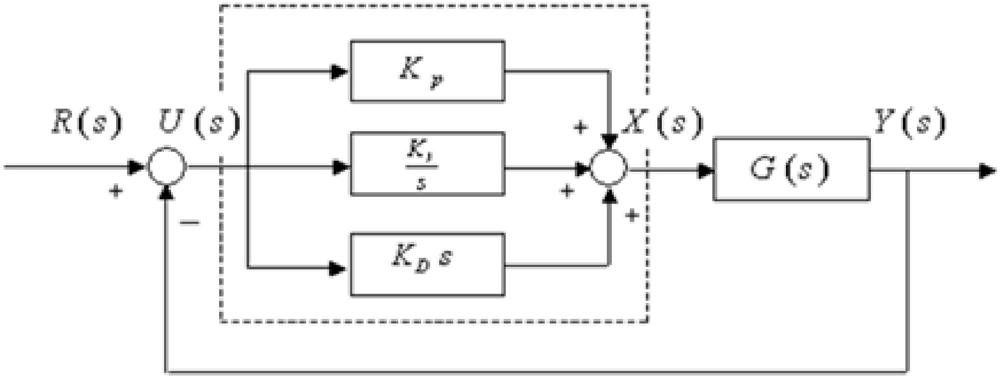
In this paper, two approaches namely the proportional-integral-derivative (PID) and linear quadratic regulator (LQR) controllers are considered for controlling the DC motor speed.

3.1. PID Controller

The main concept of a PID control involves measuring the error of a system, calculating the control input by computing proportional, integral, and derivative terms, and finally aggregating the three terms to be fed to the system [14]. The proportional gain K_P minimizes the rising time and steady state error. The integral gain K_I removes the steady state error with an effect on transient response. The derivative gain K_D improves the system stability, minimizes overshoot and improves the transient response. Figure 5 shows the block diagram of a PID controller and the transfer function of a PID controller is stated as

$$G_c = K_p + \frac{K_i}{s} + K_d s \tag{12}$$

Figure-5. Block diagram of a PID controller



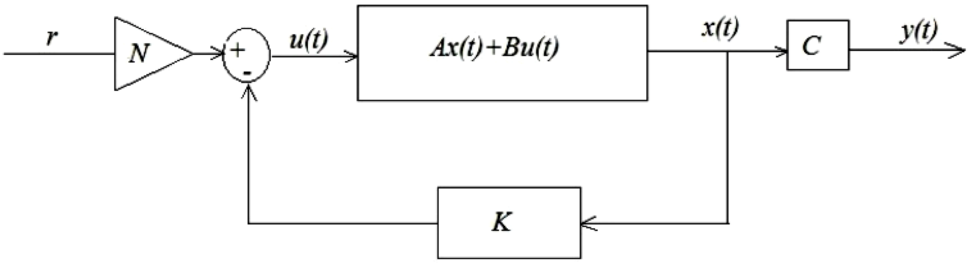
3.2. LQR Controller

The LQR controller utilizes an algorithm that minimizes a performance index *J* and the control effort with weighting factors that are supplied by a designer [15]. The performance index can be described as

$$I = \int_0^{\infty} (X^T(t)Qx(t) + u^T(t)Ru(t)) \quad (13)$$

Where X^T refers to a state vector and u^T is an input vector, *Q* and *R* are positive definite (or positive semi-definite) state cost and performance matrices respectively. The performance index is tuned until a desired performance is reached, after which a feedback gain of the control system is computed. After suitable values of *Q* and *R* are chosen, controller gains are calculated using the *lqr* function in MATLAB. Figure 6 depicts the block diagram of an LQR controller.

Figure-6. Block diagram of an LQR controller



4. Result and Discussion

A mathematical model has to be validated by comparing simulated and experimental data, before it could be used for simulation and control purposes. Figure 7 shows a random voltage that is applied as the input for both the simulation model and actual DC motor. Simulated and actual speed response is presented in Figure 8.

Figure-7. Random input voltage

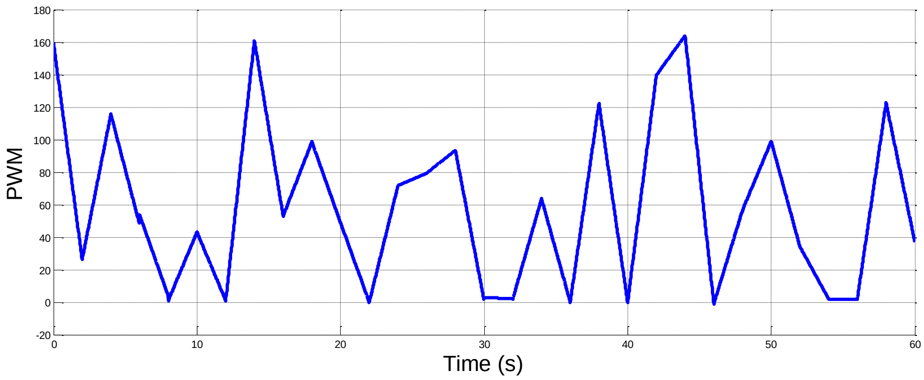
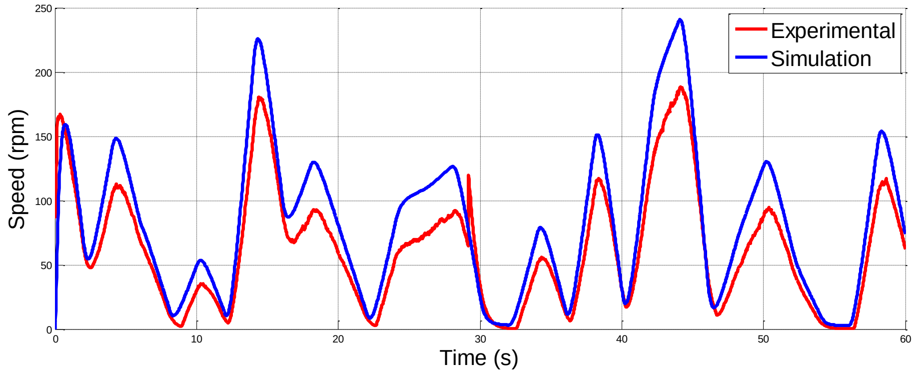


Figure-8. Speed response comparison



Analyzing the figures above, it can be observed that the angular speed curves from the simulation is close to that of measured from the experiment.

The experimental speed responses for step and square reference inputs are shown in Figs. 9 and 10 respectively. The input to the DC motor is in the form of pulse width modulation (PWM). The range of PWM from 0 to 255, which is equivalent to 0 to 12V.

Figure-9. Response for step wave input

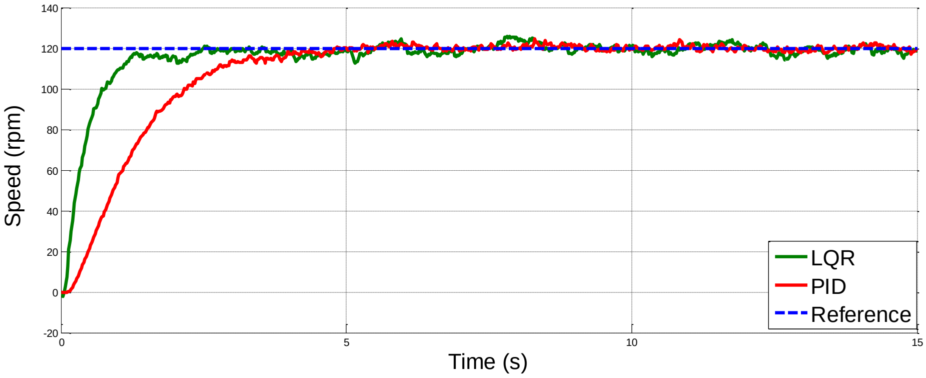
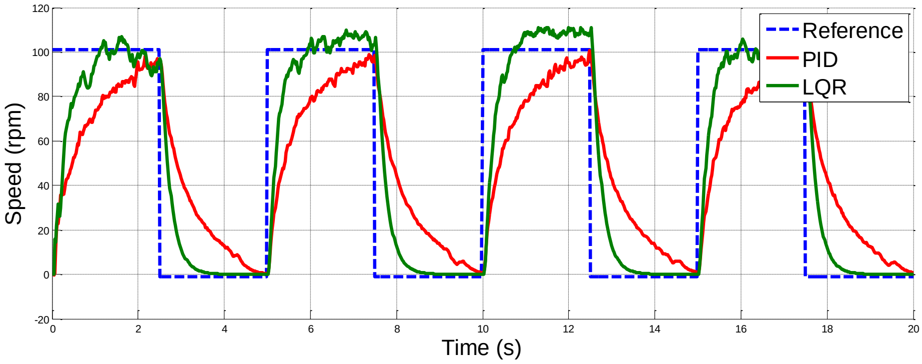


Figure-10. Response for square wave input



5. Conclusion

The mathematical model of a DC motor is derived by implementing the system identification method. The process is achieved with a simple and cheap data accusation system. The mathematical model is validated, after which PID and LQR controllers are designed based on the derived model. Practical experiments are carried out to test the performances of the controllers for angular speed control. Experimental results indicate that the LQR controller performs better than the PID controller.

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