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Precise angular speed control of permanent magnet DC motors in presence of high modeling uncertainties via sliding mode observer-based model reference adaptive algorithm

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ABSTRACT

The major concentration of this study is on developing a control scheme with parameter- and load-insensitive features capable of precise angular speed regulation of a permanent magnet (PM) DC motor in the presence of modeling uncertainties. Towards this objective, first, an appropriate nonlinear dynamic model of friction, the modified LuGre model, is opted and incorporated into the mathematical model of a PM DC motor. Then a sliding mode observer (SMO) is designed to estimate the state variable of the friction model. Next, a model reference adaptive control system into which estimated values of the friction state and parameters are fed is designed to track the desired speed trajectory while alleviating the adverse effects of model uncertainties and friction. Stability of the proposed SMO-based MRAC system is discussed via the Lyapunov stability theorem, and its asymptotic stability is verified. In addition to simulation studies, the algorithm is implemented on a new variable structure test-bed which gives us the ability to simulate desired parameter variations and external disturbance changes in experiment. The main contribution of the proposed scheme is the bounded estimation of the system's friction parameter. While similar control solutions do estimate these parameters, there is no guarantee that they will estimate the correct value of friction parameters. However, in the proposed method, by properly choosing the design parameters, if certain criteria is satisfied, the estimated friction parameters will be in the bounded vicinity of their actual values. The obtained results show the effectiveness of the proposed tracking algorithm and its robustness against load and system parameters' variations.

1. Introduction

Escalating demands for servo systems in robotics, portable machine tools, aircraft and electric traction industries raise a need for high precision position and speed controls. In addition to accuracy, disturbance rejection, load/friction compensation and robustness against parameters variations should be considered in designing such controllers. Also, stability is another aspect which needs to be deemed in both theory and real implementation. Since uncertainty analysis needs rigorous mathematical efforts, its influences in controller design are ignored sometimes. Steady state error, occurrence of instability and limit cycle oscillation may be possible due to existence of uncertainties. Therefore, regardless of the arduous mathematical efforts needed, it is imperative that uncertainty as a factor that reduces the accuracy and overall performance of servo systems should be addressed in the controller design. Uncertainties in systems can include unmodeled dynamics, unknown external disturbances, parameter variations, friction, etc.

Owing to uncertainties' practical importance, a copious amount of researches are focused on how to compensate and reduce its effects. Different types of controllers such as proportional–integral–derivative (PID) controller [1], integral controller [2], dither controller [3], reduced-order observer based controller [4], model reference adaptive control [5] and impulsive control [6] have been used to reduce the effects of uncertainties, and have resulted in significant enhancement of the regulation performance and accuracy. Whereas, the aforementioned regulators may lead to high-gain controllers which can in turn result in high sensitivity to sensors' noise and excitation of unmodeled dynamics.

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Generally, the objective of controllers is to find the optimum set of regulating commands to make the system reach the desired states with minute deviations. In systems where friction plays a substantial role, this can be interpreted as taking the friction value into account. There are many researches related to the modeling of friction dynamic and compensation techniques in diverse operation conditions [7–10]. The existing friction models can be generalized in two main categories: static and dynamic [11]. In the static models [12,13], in standstill condition, there is no relative velocity between the bodies in contact. However, from dynamic models' point of view [14–18], small presliding happens in that case. Both of these categories describe the same friction force as a function of surfaces' relative velocity when it is more than 0.003 m/s [19]. Based on what the application is, each of the static or dynamic models can be considered. Static models are utilized when high slip velocities happen, and the number of transitions between stand still and kinetic friction states are small and rapid. Generally, when precise control is the case, dynamic models are better options which deem both friction regimes [20]. In dynamic models, standstill friction conditions and both small and high slip velocities are considered. The main disadvantages of dynamic models are their complexity and the high computation burden that they impose on the hardware in real time regulation. Among different models of friction, the LuGre model explained intensively in [21,10,14] is a nonlinear friction model which is capable of modeling both the static and dynamic aspects of friction. Compared to other friction models, since the mentioned friction model's behaviors are closer to the actual behavior of friction under different operation conditions, they are utilized in many researches [22–24].

Much research is done in the area of friction compensation. Various modern controllers with a focus on speed/position control have been used to cope with disturbance in servo systems. Some examples of these controllers are adaptive controller [25,26], state feedback regulation [27] and robust control [28]. Fuzzy and neural networks algorithms have been also utilized in this field of research to control servo actuators with regards to reducing the demerits of friction by employing estimation techniques [29–31]. Along with diverse types of adaptive controllers, model reference adaptive controllers (MRAC) have addressed the problem of friction compensation more effectively [32,25] and can be an appropriate choice for industrial applications. MRAC is an apt option when a system's model is approximately identified and disturbance dynamic is assessable. In the MRAC, meanwhile using the error between the output of a real plant and its model to adjust the controller parameters so that the system can track a desired path, parameters of the controller converge to some values. By using model's parameters and these obtained values, parameters of the system are attainable. As mentioned in [33], even though there is no guarantee that these attained parameters will reach their true values, the regulator tracks the desire path precisely. Since most industrial processes are highly nonlinear and have various types of uncertainties, disturbances and load, performance of the linear MRAC may deteriorate. Unless, the nonlinearities of the plant such as friction are assessed and addressed sufficiently in model of the system. In the LuGre model, there is a state $z(t)$ which is not physically measurable and can be assumed as a virtual state that needs to be estimated by application of an appropriately designed observer. In [34], an observer is used in a closed-loop feedback system to estimate the $z(t)$, but the parameters of friction are assumed to be known. As an acclaimed research on friction compensation, an adaptive control scheme is proposed in [25] for friction reduction while utilizing the LuGre model and a sliding mode observer. However, in [25], despite the precise control, there is no guarantee for convergence of the estimated friction parameters to their true values. It is also worth noting that among various kinds of observers, sliding mode observer (SMO) is the one highly robust against bounded parameters uncertainties [35,36].

In this paper, an observer-based model reference adaptive controller is proposed to track desired speed path by attenuating the adverse effects of friction. Besides simulation, robustness of the proposed algorithm against parameter/structure and load changes is tested by implementing it on a new variable structure test-bed including four permanent magnet DC motors. The obtained results indicate that the proposed method is able to effectively compensate friction and load and is robust against parameter/structure variations. Furthermore, the stability of the proposed controller is assessed using the Lyapunov stability theorem.

2. Problem statement

2.1. Linear DC motor model

The permanent magnet DC motors are widely used for precise speed/position control due to their accurate voltage regulation and ease of driver design. The servo system employed in this research is the PM brushed DC motor. Four of these motors are used in the form of a variable structure test-bed to assess the robustness and performance of the proposed adaptive controller against parameter and/or load changes. The PM DC motor equivalent circuit is shown in Fig. 1. According to Fig. 1, by writing the voltage and torque balance equations for the system, the governing dynamic equations of PM DC motors are as (1) and (2).

$$J\ddot{x} = -B\dot{x} + k_t i - T_L \quad (1)$$

$$L_a\dot{i} = -k_e\dot{x} - R_a i + u \quad (2)$$

If the value of DC motor's electrical time constant is small, i.e. $\frac{L_a}{R_a} \approx 0$, which is the case in this study according to Appendix A, by considering $\frac{di_a}{dt} \approx 0$, Eq. (2) is simplified as

$$i = \frac{u - k_e\dot{x}}{R_a}. \quad (3)$$

By substitution of (3) in (1), a second-order linear differential equation for the PM DC motor is derived as (4).

$$J\ddot{x} = \left(-B - \frac{k_t k_e}{R_a}\right)\dot{x} + \frac{k_t}{R_a}u - T_L \quad (4)$$

$\dot{x}(t)$ (rad/s) and $\ddot{x}(t)$ (rad/s^2) are the angular velocity and acceleration of the motor, respectively. $i(t)$ (A) is the armature current, $u(t)$ (V) is the terminal voltage of armature circuit and T_L (N m) is the motor's shaft load. Moreover, J (Kg m^2) is the inertia moment of

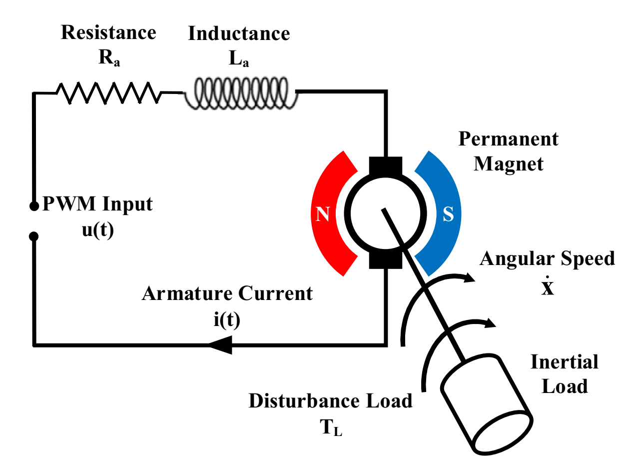

Fig. 1. PM DC motor equivalent circuit.