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ORIGINAL ARTICLE

Adaptive PID control of a stepper motor driving a flexible rotor

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Abstract Stepping motors are widely used in robotics and in the numerical control of machine tools to perform high precision positioning operations. The classical closed-loop control of the stepper motor can not respond properly to the system variations unless adaptive technique is used. In this paper, the feasibility of fuzzy gain scheduling control for stepping motor driving flexible rotor has been investigated and illustrated by numerical simulation. The proposed control was concerned with the permanent magnet step motor (PMSM) with mechanical variations such as stiffness of rotor and load inertia. A mathematical model for the PMSM was derived and the gains of a conventional PID control were presented. The data base required in learning process of the fuzzy logic gain scheduling mechanism was obtained from the mathematical model. It was found that the stable value for the integral gain is half the value of the proportional gain. The fuzzy systems for scheduling the derivative gain and the proportional gain are presented. The conducted simulation showed that the fuzzy system is able to adapt the controller gains to track the desired load and speed response. Fuzzy PID performance is much better than the conventional PID control scheme. Fuzzy self-tuning controller demonstrates a very fast response and little overshoot.

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1. Introduction

Mechatronics is defined as the interdisciplinary field of engineering that deals with the design of products whose function relies on the integration of mechanical, electrical, and electronic components [1,2]. Actuators (motors) are considered as essential components of all Mechatronics systems. Stepper motors are widely implemented in systems that demand high accuracy combined with quick response [3]. Stepping motors were mainly used for simple point-to-point positioning tasks in which they were open-loop controlled. In this way, they were driven by a pulse train with a predetermined time interval between successive pulses applied to the power driver, and no information on the motor shaft position or speed was used [4,5]. Unfortunately, the open-loop control scheme suffers from low-performance capability and lack of adaptability to load variations and system variations. Indeed, without feedback, there is no way of knowing if the motor has missed a pulse or if the speed response is oscillatory. The closed-loop principle [6] was introduced in order to increase the accuracy positioning of the stepping motor while making it less sensitive to load disturbances. The closed-loop control is characterized by starting the motor with one pulse, and subsequent drive pulses are generated as a function of the motor shaft position and/or speed by the use of a feedback encoder. Nowadays, due to advances made in both power electronics and data processing, stepping motors are more often closed-loop controlled, in particular, for machine tools and robotic manipulators in which they have to perform high precision operations in spite of the mechanical configuration changes. Also, the use of classic closed-loop algorithms such as Proportional-integral-derivative (PID) control is weak unless the closed-loop control is forced to adapt to the motor operating conditions. Fuzzy Logic [7–9] is a technology of great potential in the fields of artificial intelligence and Mechatronics. It mimics the human way of thinking and decision-making. Fuzzy PID control can be classified into two major categories according to their construction [10]. One category has no explicit proportional, integral, and derivative gains; instead the control signal is directly deduced from knowledge base and fuzzy inference. Most of the research on fuzzy logic control design belongs to this category [11–14]. Another category is fuzzy-scheduling of conventional PID gains. In recent years, fuzzy-scheduling control has been widely applied to solve versatile control problems. Zhao and Collins [15] designed fuzzy PI controller for weigh belt feeder to maintain a constant feed rate. They used singleton TS fuzzy model based on the error and the change in error as inputs to tune the proportional and integral gains. Chang et al. [16] proposed fuzzy scheduling control scheme, including the feedback states and the integral of tracking error for induction servo motor. Regional stability was discussed upon considering the saturation phenomena of the actuator. Hazzab et al. [17] presented control of an induction motor using fuzzy gain scheduling of PI controller based on tracking error and its first time derivative. Chang et al. [18] applied fuzzy-scheduling control to a linear permanent magnet synchronous motor with pay load variations. They implemented the technique adopted in [16]. Allaoua et al. [19] studied DC motor scheduling PID control with particle swarm optimization strategy and compared the results with those of fuzzy logic controller. Ghafari and Alasty [20–22] implemented gain scheduling PID fuzzy controller for hybrid stepper motor. He did not consider rotor flexibility nor load variations (Fig. 1).

The aim of this paper is to investigate the feasibility of a fuzzy PID control for a stepping motor drive of flexible rotor and to evaluate its sensitivity for mechanical configuration changes. The simulation allows the generation of load torque and inertia variations, which are the main disturbances, found in the control machine tools and robotic manipulators. These two mechanical variations are generated in order to test the system response to external disturbances and the effectiveness in the plant parameters. The scope of this work is limited to the study of the control of permanent magnet stepper motor (PMSM).

2. System mathematical model

2.1. Modeling of a permanent magnet stepper (PMS) motor

This section provides a brief derivation of a nonlinear model of the 2-phase PM stepper motor. A number of references are available on the generation of stepper motor model [1,2].

The rotor shaft dynamics are given by:-

$$J_m \frac{d\omega}{dt} = T_m - F\omega - T_L \qquad (1)$$

J_m = Total inertia of the rotor, F = Viscous friction coefficient, T_L = Load torque.The angular velocity is given:-

The above Eq. (1) forms the basis for a general rotor dynamics model of a PM stepper motor. Hence for a 2 phase PM motor with P rotor pole pairs and the two phases (φ_j) at 0 and ($\pi/2$) the following state space equations can be derived.

$$\begin{aligned} \frac{d\theta}{dt} &= \omega \\ \frac{d\omega}{dt} &= \frac{K_m}{J_m}(-i_a \sin P\theta + i_b \cos P\theta) - \frac{F}{J_m}\omega - \frac{T_L}{J_m} \\ \frac{di_a}{dt} &= -\frac{R}{L} i_a + \frac{K_m}{L}\omega \sin P\theta + \frac{u_a}{L} \\ \frac{di_b}{dt} &= -\frac{R}{L} i_b - \frac{K_m}{L}\omega \cos P\theta - \frac{u_b}{L} \end{aligned} \qquad (2)$$

where, ω is the angular velocity, $\frac{d\omega}{dt}$ is the load acceleration, $\frac{di_a}{dt}$ is the current through winding a, $\frac{di_b}{dt}$ is the current through winding b.

2.2. Flexible shaft

Considering the case when the load is connected to the motor through a long stiff shaft with stiffness k, then the motor inertia will be J_m and the load inertia will be J_L as shown in Fig. 3.

In this case, the load and flexible shaft equation will be:-

$$\frac{d\theta_L}{dt} = \omega_L \qquad (3)$$

$$\frac{d\omega_L}{dt} = \frac{1}{J_L}[(-k(\theta_L - \theta_m) - B(\omega_L - \omega_m))]$$

A classical control technique for PMSM is based on park's transformation [1]. That is, the transformation of the vector (u) and (i) expressed in the fixed stator frame (a, b) into vectors expressed in a frame (d, q) that rotates along the fictitious excitation vector such that:

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \begin{bmatrix} \cos P\theta & \sin P\theta \\ -\sin P\theta & \cos P\theta \end{bmatrix} \begin{bmatrix} X_a \\ X_b \end{bmatrix}$$

The state Eq. (2) expressed in terms of currents and voltages in rotating (d, q) coordinates become:

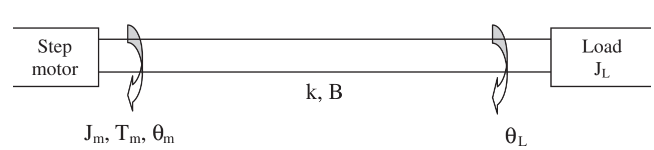

Figure 1 Flexible rotor system.