Automatica 45 (2009) 2890–2896

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Brief paper

Adaptive robust control of linear motors with dynamic friction compensation using modified LuGre model[☆]

Lu Lu[a], Bin Yao[b,a,*], Qingfeng Wang[a], Zheng Chen[a]

[a] The State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou, 310027, China

[b] School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 23 March 2008
Received in revised form
15 August 2009
Accepted 31 August 2009
Available online 22 October 2009

Keywords:
Dynamic friction
LuGre model
Motion control
Linear motor
Adaptive robust control

ABSTRACT

LuGre model has been widely used in dynamic friction modeling and compensation. However, there are some practical difficulties when applying it to systems experiencing large range of motion speeds such as, the linear motor drive system studied in the article. This article first details the digital implementation problems of the LuGre model based dynamic friction compensation. A modified model is then presented to overcome those shortcomings. The proposed model is equivalent to LuGre model at low speed, and the static friction model at high speed, with a continuous transition between them. A discontinuous projection based adaptive robust controller (ARC) is then constructed, which explicitly incorporates the proposed modified dynamic friction model for a better friction compensation. Nonlinear observers are built to estimate the unmeasurable internal state of the dynamic friction model. On-line parameter adaptation is utilized to reduce the effect of various parametric uncertainties, while certain robust control laws are synthesized to effectively handle various modeling uncertainties for a guaranteed robust performance. The proposed controller is also implemented on a linear motor driven industrial gantry system, along with controllers with the traditional static friction compensation and LuGre model compensation. Extensive comparative experimental results have been obtained, revealing the instability when using the traditional LuGre model for dynamic friction compensation at high speed experiments and the improved tracking accuracy when using the proposed modified dynamic friction model. The results validate the effectiveness of the proposed approach in practical applications.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Friction modeling and compensation have been studied extensively, but is still full of interesting problems due to their practical significance and the complex behavior of friction. It has been well known that to have high accuracy of motion control at low speed movement, friction cannot be simply modeled as a static nonlinear function of velocity alone, but rather a *dynamic* function of velocity and displacement. Thus, during the past decade, significant efforts have been devoted to solve the difficulties in modeling and compensation of dynamic friction with various types of models proposed (Canudas de Wit, Olsson, Astrom, & Lischinsky, 1995; Dupont, Armstrong, & Hayward, 2000; Lampaert, 2003). Among them, the so called LuGre model by Canudas de Wit et al. (1995) can describe major features of dynamic friction, including presliding displacement, varying break-away force and Stribeck effect. In Olsson (1996), the modification for passivity has been added into the LuGre model. Dupont et al. (2000) proposed a modification for the LuGre model, which can describe the non-drifting effect of dynamic friction. In Swevers, Al-Bender, Ganseman, and Prajogo (2000), a so called Leuven model was proposed, which added the modeling of hysteresis into the LuGre model. But both Dupont et al. (2000) and Swevers et al. (2000) complicated the form of the friction models significantly and make them harder to use for real-time controls.

Due to its relatively simpler form and its ability to simulate major dynamic friction behaviors, LuGre model has been widely used in control with dynamic friction compensation (Canudas de Wit & Lischinsky, 1997; Tan & Kanellakopoulos, 1999; Xu & Yao, 2008). Although many good application results have been reported (Bona, Indri, & Smaldone, 2006), some practical problems are also discovered, especially when applying the LuGre model to systems experiencing large ranges of motion speeds such as, the linear motor

[☆] The work is supported in part by the US National Science Foundation (grant No. CMS-0600516) and in part by the National Natural Science Foundation of China (NSFC) under the Joint Research Fund for Overseas Chinese Young Scholars (grant No. 50528505). The material in this article was not presented at any conference. This article was recommended for publication in revised form by Associate Editor Yong-Yan Cao under the direction of Editor Toshiharu Sugie.

[*] Corresponding address: School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA. Tel.: +1 765 494 7746; fax: +1 765 494 0539.

E-mail addresses: lulu.lvlv@gmail.com (L. Lu), byao@purdue.edu (B. Yao), qfwang@zju.edu.cn (Q. Wang), cwlinus@gmail.com (Z. Chen).

0005-1098/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.automatica.2009.09.007

drive system studied in this article. Namely, the traditional LuGre model could become very stiff when the velocity is large. This leads to some unavoidable implementation problems, since dynamic friction compensation can be only implemented digitally due to its highly nonlinear characteristics. For example, it has been reported in Freidovich, Robertsson, Shiriaev, and Johansson (2006) that the observer dynamics to recover the unmeasurable internal state of the LuGre model could become unstable at high speed motions.

On the other hand, no matter how accurate the mathematical models of dynamic friction are, it is impossible to capture the entire nonlinear behaviors of actual friction to have a perfect friction compensation. So, advanced control techniques have to be used in parallel with appropriate selection of dynamic friction models for effective friction compensation and attenuation. A good control algorithm should have features of both strong disturbance rejection and performance robustness to model uncertainties as well as the ability of on-line learning (e.g., parameter adaptation) in reducing model uncertainties to maximize the achievable control performance. The idea of adaptive robust control (ARC) (Yao & Tomizuka, 1996, 1997) incorporates the merits of deterministic robust control (DRC) and adaptive control (AC) and serves well to meet such a requirement. It is noted that the proposed ARC strategy has been well validated in various applications without having any dynamic friction compensations (Hong & Yao, 2007; Xu & Yao, 2001; Yao, Bu, Reedy, & Chiu, 2000).

In this article, we first revisit the LuGre model and discuss the digital implementation problems when using the model for dynamic friction compensation. Based on the analysis, a modified version of LuGre model is proposed for dynamic friction compensation, in which the estimation of internal states is automatically stopped at high speed movements to by-pass the instability problem of the LuGre model based observer dynamics. A continuous function is designed to make a continuous transition from the LuGre model based low speed dynamic friction compensation to the static friction model based high speed friction compensation. We then utilize the ARC strategy along with the proposed modified LuGre model based dynamic friction compensation to achieve accurate trajectory tracking for both low-speed and high-speed movements. The proposed ARC algorithm, along with ARC algorithms with friction compensations using the LuGre model and the static friction model, respectively, are tested on a linear motor driven industrial gantry system. Comparative experimental results are presented to illustrate the effectiveness of the proposed modified LuGre model based dynamic friction compensation in practical applications and the excellent tracking performance of the proposed ARC algorithm.

2. Dynamic model of linear motor systems

The linear motor dynamics can be captured well by Lu, Chen, Yao, and Wang (2008)

$$\dot{x}_1 = x_2 \tag{1}$$

$$m\dot{x}_2 = u - f + \bar{\Delta} \tag{2}$$

where $x = [x_1\, x_2]^{\mathrm{T}}$ represents the state vector consisting of the position and velocity, m denotes the inertia of the system normalized with respect to the control input unit of voltages, $u(t)$ is the control input, f represents the normalized friction, and $\bar{\Delta}$ represents the lumped unknown nonlinear functions including the friction modeling errors and the external disturbances. For certain linear motors with permanent magnets, it may be necessary to explicitly consider the effect of cogging forces when the desired trajectory spans a large travel distance. Here, to focus on the main issue of dynamic friction compensation, for simplicity of presentation and without loss of generality, the effect of cogging forces is not explicitly modeled and is lumped into the lumped uncertainties term $\bar{\Delta}$. Using the technique in Lu et al. (2008), the effect of cogging forces can be incorporated easily into the proposed control algorithm as done in some of the experimental results detailed later.

3. Modified LuGre model and problem formulation

With the LuGre model (Canudas de Wit et al., 1995), the friction f in (2) is given by

$$f = \sigma_0 z + \sigma_1 h(v)\dot{z} + \alpha_2 v \tag{3}$$

$$\dot{z} = v - \frac{|v|}{g(v)} z \tag{4}$$

$$g(v) = \alpha_0 + \alpha_1 \mathrm{e}^{-(v/v_s)^2} \tag{5}$$

where z represents the unmeasurable internal friction state, σ_0, $\bar{\sigma}_1(v) = \sigma_1 h(v)$, α_2 are constant or varying friction force parameters that can be physically explained as the stiffness, the damping coefficient of bristles, and viscous friction coefficient. $v = x_2$ is the velocity of linear motor. The function $g(v)$ is positive and it describes the Stribeck effect: $\sigma_0\alpha_0$ and $\sigma_0(\alpha_0 + \alpha_1)$ represent the levels of the Coulomb friction and stiction force, respectively, and v_s is the Stribeck velocity. It is shown in Olsson (1996) that the LuGre model is passive if $\sigma_1 h(v) < \frac{4\sigma_0 g(v)}{|v|}$, where $h(v)$ is an exponentially decay or fractionally decay function with respect to velocity, satisfying $h(v) < h(0) = 1$.

Direct use of the above LuGre model for friction compensation may have some implementation problems. Namely, as the internal friction state z is unmeasurable, it is necessary to construct observers to estimate z for dynamic friction compensation. With LuGre model, the observe dynamics would be of the form of

$$\dot{\hat{z}} = v - \frac{|v|}{g(v)}\hat{z} + \gamma\tau \tag{6}$$

where γ represents the observer gain and τ is the observer error correction function to be selected. Since the observer dynamics (6) are highly nonlinear, the only way to implement the observer is through microprocessors using its discretized version assuming certain sampling rate. With the digital implementation of (6), to avoid instability due to discretization with a finite sampling rate, it is necessary that the equivalent gain $\frac{|v|}{g(v)}$ in (6) is not too large. In Freidovich et al. (2006), it is shown that if the velocity exceeds a critical value which is proportionally related to the sampling rate, digital implementation of the above observer dynamics will become unstable.

On the other hand, the dynamic friction effect is noticeable only when the relative velocity is low. For high speed motions, it is enough to use the following traditional static friction model:

$$f = F_c \mathrm{sgn}(v) + F_v v. \tag{7}$$

It should be noted that at constant speed motion, F_c is related to $\sigma_0|z_{ss}|$ and F_v is related to α_2 in (3)–(5). It is worth noting that Canudas de Wit (1998) also briefly mentioned the possibility of stopping the integration of z and using its steady-state value $\hat{z}_{ss} = \frac{F_c}{\sigma_0}\mathrm{sgn}(v)$ when the speed is above certain critical value. In this case, the friction term is exactly the same as (7). But this rather simplistic modification may result in discontinuous internal state estimation when the speed transits between high and low ranges. In addition, no experimental results have been provided to validate such a modification. With all these facts in mind, in the following, a modified LuGre model will be proposed, which is essentially equivalent to LuGre model (3) at low speeds, and the static friction model (7) at high speeds, with a continuous transition between these two models from low speeds to high speeds. Specifically, the proposed modified model has the form of

$$f = \sigma_0 s(|v|) z + \sigma_1 h(v)\dot{z} + F_c \mathrm{sgn}(v)[1 - s(|v|)] + \alpha_2 v \tag{8}$$

$$\dot{z} = s(|v|)\left(v - \frac{|v|}{g(v)} z\right) \tag{9}$$

$$g(v) = \alpha_0 + \alpha_1 \mathrm{e}^{-(v/v_s)^2} \tag{10}$$

where $s(|v|)$ is a non-increasing continuous function of $|v|$ with the

Download English Version:

https://daneshyari.com/en/article/697698

Download Persian Version:

https://daneshyari.com/article/697698

Daneshyari.com