A ROBUST NON MODEL-BASED FRICTION COMPENSATION APPROACH

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Abstract: A robust friction compensation approach is proposed, constituted by a feedback control law, including the compensation of the friction effects, on the basis of the estimate provided by a non model-based, reduced-order observer. The approach, developed in the paper to solve a regulation problem for a 1-dof servomechanism, does not require the knowledge of the friction parameters. The stability properties of the controlled system, and the robustness of the proposed control scheme with respect to variations of the system inertia, are analytically proven, and confirmed by simulation results. *Copyright IFAC 2006©*

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1. INTRODUCTION

Friction compensation is crucial in robotics to avoid undesirable effects such as stick-slip motions, limit cycles and hunting in the stopping phase of the robot motion, or significant tracking errors at low velocities. Several solutions have been proposed in literature for friction compensation (see (Bona and Indri, 2005) and the references therein), following different approaches. Some control schemes, e.g., in (Kostić *et al.*, 2004), (Putra *et al.*, 2004), and (Moreno *et al.*, 2003), are based on the insertion of a 'fixed' compensation term, determined by estimating off-line the parameters of the model chosen to describe friction. The main drawbacks of this kind of solution are given by the accuracy required in the friction identification phase (possibly performed by using high-precision sensors), and by the impossibility to account for friction variations. Model-based adaptive algorithms are then often applied for on-line friction compensation, e.g. in (Canudas de Wit and Lischinsky, 1997), (Vedagarbha *et al.*, 1999), (Feemster *et al.*, 1999), (Hung *et al.*, 2002), at the price of a greater computational burden, but, since only some of the friction parameters can be easily updated online, an initial identification procedure must be performed anyway. To overcome these difficulties, different, non model-based strategies have been proposed to counteract the friction effects, e.g., by properly choosing the control gain parameters, as in (Armstrong *et al.*, 2001), or by using non model-based observers, as in (Chen *et al.*, 2000). In particular, the solution developed in (Chen *et al.*, 2000) is based on the insertion of a nonlinear disturbance observer, considering friction as a disturbance acting on the control torque, together with other unknown torques (without referring to a specific friction model), under the assumption that such a disturbance term varies slowly with respect to the observer dynamics (thus assuming it as practically constant).

The control approach proposed in this paper is constituted by a feedback control law, including the compensation of the friction effects, on the basis of the estimate provided by a non model-based, reduced-order observer. For the sake of simplicity, the analysis is carried out to solve a regulation problem in the case of a 1-dof servomechanism, but the approach can be extended to multi-dof systems. Friction is assumed to be described by the nonlinear, static part of the LuGre model (Canudas de Wit *et al.*, 1995), but its knowledge is not necessary in practice to guarantee the global asymptotic stability property of the closed-loop system, which is analytically proven in two cases: (*i*) when the inertia of the servomechanism is known, and (*ii*) when only an estimate of the actual inertia is available. The effectiveness of the proposed control approach and its robustness with respect to variations of the system inertia are confirmed by simulation results.

2. SYSTEM MODELLING AND CONTROL PROBLEM STATEMENT

Consider a 1-dof servomechanism, subject to friction, whose dynamic behavior is described by:

$$J\ddot{q}(t) = F_c(t) - F_f(t), \qquad (1)$$

where J is its inertia, $q(t)$ is the generalized position coordinate, $F_c(t)$ is the command generalized force (or torque), and $F_f(t)$ is the friction generalized force (or torque). Friction is assumed to be described by the nonlinear, static part of the LuGre model (Canudas de Wit *et al.*, 1995), (Canudas de Wit and Lischinsky, 1997):

$$F_f(v(t)) = \left[\alpha_0 + \alpha_1 \mathrm{e}^{-\left(\frac{v(t)}{v_0}\right)^2}\right] \mathrm{sgn}(v(t)), \qquad (2)$$

where $v(t) = \dot{q}(t)$ is the system velocity, $v_0 > 0$ is the *Stribeck velocity*, defining the velocity range in which the Stribeck effect dominates the friction behavior, and α_0, α_1 are positive parameters (in particular, the initial stiction value is given by $\alpha_0 + \alpha_1$).

Goal of this work is the development of a control algorithm that does not require the complete knowledge of the friction characteristics, such that the convergence of the system position $q(t)$ to an assigned, constant value q_r is globally asymptotically achieved (i.e., a control algorithm suitable to solve a *regulation* problem). Such a problem is quite interesting in practice, since the presence of the Stribeck effect often causes limit cycles and instabilities just in the stopping phase, when velocity tends to zero (see e.g. (Kermani *et al.*, 2004)).

3. THE PROPOSED CONTROL APPROACH

The proposed control approach is constituted by a feedback control law, including the compensation of the friction effects, on the basis of the estimate provided by a reduced-order observer. Similar approaches have been already employed successfully in (Tornambè, 1996), (Indri and Tornambè, 1999), and (Indri and Tornambè, 2000) to counteract the impact effects in case of mechanical systems or robots subject to smooth impacts.

The proposed approach is developed in two cases: (*i*) when the inertia J of the servomechanism is known; (*ii*) when only an estimate $\hat{J}$ of the actual inertia J is available. In the last case, the same reduced-order observer is used to estimate also the effects of the inexact inertia parameter used in the feedback law.

3.1 Friction compensation with exact knowledge of the inertia parameter

For the following developments, it is useful to define the command generalized force $F_c(t)$ as:

$$F_c(t) = Ju(t), \qquad (3)$$

where J is supposed to be exactly known, and $u(t)$ will be defined according to the proposed control approach developed hereafter.

The equation of motion (1) of the system can be recast in state variable form, considering $[q(t)\ v(t)]^T$ as state vector, as:

$$\dot{q}(t) = v(t), \qquad (4a)$$

$$\dot{v}(t) = u(t) + \delta(t), \qquad (4b)$$

with

$$\delta(t) := -\frac{1}{J} F_f(v(t)). \qquad (5)$$

The proposed control scheme is described by the following equations:

$$u(t) = -K_p(q(t) - q_r) - K_v v(t) - \hat{\delta}(t), \qquad (6a)$$

$$\hat{\delta}(t) = \xi(t) + \mu v(t), \qquad (6b)$$

$$\dot{\xi}(t) = -\mu\xi(t) - \mu^2 v(t) - \mu u(t), \qquad (6c)$$

where K_p, K_v are positive constants such that the roots of

$$p(\lambda) = \lambda^2 + K_v\lambda + K_p \qquad (7)$$

are in the open left-half plane, and μ is a positive constant, which must be suitably chosen for stability, as it will be discussed in the remainder of this section. The control law (6a) is constituted by a PD part and by the term $\hat{\delta}(t)$, which compensates for the friction effects on the basis of the estimate provided by the reduced-order observer (6b), (6c).

Let $e(t) := q(t) - q_r$ be the generalized position error. The closed-loop system (4)-(6) thus obtained can be written, after some manipulation, as:

$$\dot{e}(t) = v(t), \qquad (8a)$$

$$\dot{v}(t) = -K_p e(t) - K_v v(t) + \tilde{\delta}(t), \qquad (8b)$$

$$\dot{\tilde{\delta}}(t) = \mu\tilde{\delta}(t), \qquad (8c)$$

where $\tilde{\delta}(t) = \delta(t) - \hat{\delta}(t)$.

Besides, let function $D_F(v)$ be introduced as:

$$D_F(v) = -2\,\frac{|v|}{v_0^2}\,\alpha_1 \mathrm{e}^{-\left(\frac{v}{v_0}\right)^2}; \qquad (9)$$