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Piecewise affine modeling and compensation in motion of linear ultrasonic actuators

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ABSTRACT

Ultrasonic actuators used in high-precision mechatronics possess strong frictional effects, which are among the main problems in precision motion control. Traditional methods apply model-based nonlinear feedforward to compensate the friction, thus requiring closed loop stability and safety constraint considerations. In this article, model-based parametric controllers are developed to obtain an optimal positioning control for these motors. A systematic approach which uses piecewise affine models greatly simplifies the friction model compared to the traditional methods. Issues about the nonlinear effects of the friction are addressed by designing a robust control law near zero speed. These developments result in a gain-scheduling optimal input, which is simple to carry out in real-time applications. The controller is expected to improve the safety constraints and the tracking performance for actuator operation.

1. Introduction

The ultrasonic motor (USM) is a type of piezoelectric actuator which uses some form of piezoelectric material and relies on the piezoelectric effect. The USM offers the advantages of high resolution and speed to ensure precision and repeatability, so it is widely used in precision engineering, robots, and medical and surgical instruments, where high accuracy is required. While a typical piezoelectric actuator (PA) is driven directly by the deformation of the piezoelectric material, the USM provides motions by the friction between the piezoelectric material on the stator and the slider. Thus, the USM offers another advantage of theoretically unlimited travel distance in comparison with the typical piezoelectric actuators.

This paper examines the USM M-663 made by *Physik Instrumente (PI)* as a testbed. Fig. 1 shows its internal structure and working principle. The slider motion is based on an alumina tip attached to the piezo-ceramic plate (the stator). This plate is segmented on one side by two electrodes. Depending on the desired direction of motion, either the left or right electrode of the piezo-ceramic plate is excited with a standing wave to produce a high-frequency vibration. Because of the asymmetry of the standing wave, the tip moves along an inclined linear path with respect to the friction bar surface and drives the slider forward or backward. Each oscillatory cycle of the tip can transfer a very small linear movement (0.3 μm) to the friction bar. With the high-frequency oscillation, this will result in a smooth and continuous slider motion. An external drive is used to convert analog input signals into the required high-frequency drive signals.

The motor is employed in a semi-automated device for medical operation on the human ear membrane. The operating parameters are: travel range $\pm$9.5 mm, maximum speed 400 mm/s and input voltage ±9 V. Because of the strict constraints in medical operation, additional control constraints arise: a tracking overshoot less than 5%, settling time within 0.1 s, maximum steady state error 0.02 mm. Controlling the actuator under such constraints and performance requirements requires specific consideration.

For control applications involving small displacements and velocities, friction modeling and compensation can be very important, especially around velocity reversal. Because the friction presents a nonlinear switch which depends on the direction of motion, using a single affine model to design a feedforward linear controller results in inaccuracy especially for low-speed control [1]. Additionally, a practical controller should respect the physical limitations of the motor input and the safety constraints on the system variables (e.g., position range, speed).

To overcome friction, the traditional control algorithms reported in the literature decouple the friction model from the linear motion system and mitigate it separately. Beside a linear regu-

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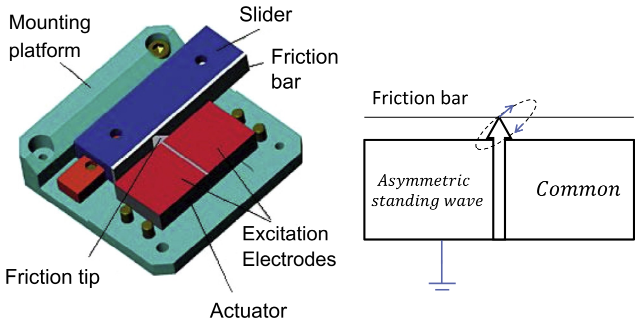

Fig. 1. Linear ultrasonic motor structure and motion description.

lator such as a PID, the input contains a nonlinear feedforward component. These methods differ from one another in the nonlinear friction models as well as the techniques to compensate for it. From this perspective, much research has focused on building accurate friction models [2–4]. The compensation, usually of bang–bang type in practice, resolves the friction problem and leaves the PID with other unmeasured disturbances including the friction model mismatch. Such approaches are simple to implement and if properly tuned, they provide fast transient response, good static accuracy, and robustness to variations in the motor parameters [5]. However, the nonlinear compensation is contingent on asymptotic stability, which relies on the specified friction model. The frictional effects can also depend on the slider position and on system degeneration, so a fixed friction model may require more computing time. Finally, such control tactics do not deal systematically with any constraints on the control input and variables, so manual safety considerations have to be taken.

To address these limitations, a hybrid model predictive control (MPC) approach, which is easy to implement and has all the advantages of model-based control, has been proposed. The flexibility of the MPC framework is that it can use mathematical programming to systematically solve a constrained optimization. An approach has recently arisen from piecewise affine (PWA) modeling of the nonlinear frictional affects to resolve friction in electrical drives. Theoretically, the idea of MPC for PWA systems was developed nicely by [6]. In the context of [7,8], the authors applied this method to design time-optimal control strategies for industrial actuators. Although the method still depends on the choice of friction models and considers no robustness, their tracking performance is promising.

In this article, a robust optimal design is adapted via the familiar quadratic programming to obtain a tractable solution. The commonly used friction models are approximated by several affine segments so that the MPC is aware of this impeding force at low speed. A constrained optimal control problem for PWA systems is then formulated to provide stability-guaranteed input. In particular, an integral MPC design imposes the robustness on any model–plant mismatch near zero-speed. Implementation of the real-time control is handled by a gain-scheduling table so that the complexity is comparable to the traditional feedforward PID.

The remainder of this article is organized as follows. Section 2 describes how the piecewise affine model can fit the shape of the friction forces. Section 3 describes model predictive control concepts in the motion tracking context. An integral MPC with robustness is also presented. Section 4 presents the results of simulation studies and experimental results. The paper is concluded in Section 5.

1.1. Notations

y, v denote the position and velocity of the motor. Ω_i $(i \in \mathbb{Z}^+)$ represents the different regions of the piecewise-affine model. F, f are the general friction and its value in these regions. A, B, C, D are matrices of state space dynamics. The indices i, j are for different system dynamics and gain-scheduling regions, respectively. All sets mentioned in this context are polyhedral sets.

2. Piecewise affine model of motion

The slider runs at ultrasonic, resonant frequencies. At microscopic level, the small linear movement of the slider induced in each movement cycle of the tip is still through friction [9]. Interesting discussion on nanoscale friction [10–12] suggested friction force is changed at high ultrasonic vibration amplitudes. In this article, it is assumed that the friction follows generalized Stribeck model (Fig. 2). In general context, the described method still works with the assumption that the friction is piecewise-affine across regions of velocity.

To model a fixed-load motion system, consider this model:

$$\begin{bmatrix} \dot{y} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ a & b \end{bmatrix} \begin{bmatrix} y \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ c \end{bmatrix} (u - F(v)), \tag{1}$$

where y, v give the slider position and velocity; $F(v)$, the friction as shown in Fig. 2, consists of the constant Coulomb friction f_c, the viscous friction $F_l = kv$, and the Stribeck effect F_{nl} which describes how the friction continuously decreases when the motor starts to accelerate [4].

The motion system of the ultrasonic motor can be represented in four regions, as in Fig. 2. Because the viscous friction is affine in v, the motion in the outer regions Ω_1 and Ω_4 can be represented by an affine equation (referred to (1)). In the inner regions Ω_2 and Ω_3, the same structure can be employed to approximate the system, but with different affine dynamics; the non-linearity in the pre-sliding regime will be addressed by the robust design in Section III.

Firstly, the asymmetric static friction values at which the motor starts moving, determined by injecting a sine wave function with low frequency and amplitude 3 V, are $f_2 = -2.9$ V and $f_3 = 2.5$ V, measured as in Fig. 3.

Secondly, the effective relation between the input and the slider position is identified at two operating ranges: very low speed and normal speed. Bi-frequency square-wave test inputs with magnitude $u = \pm 5$ V and $u = \pm 3$ V are used to stimulate the position response. The separating planes between the regions Ω_1 and Ω_2, and between Ω_3 and Ω_4 are taken at the velocity v_n, v_p obtained by applying $u = \pm 3$ V so the regions B and C encompass the nonlinear friction F_{nl}. An offset $\frac{f_2+f_3}{2}$ is added to the test input to avoid asymmetric drifting.

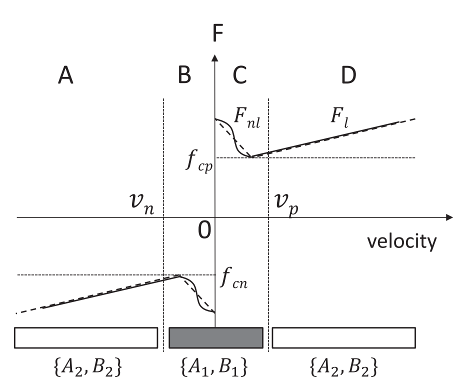

Fig. 2. Motion friction (solid) described by affine segments (dashed) over four regions, from Ω_1 to Ω_4. The outer regions Ω_1 and Ω_4 have a linear model $\{A_1, B_1\}$ while the inner regions Ω_2 and Ω_3 have $\{A_2, B_2\}$.