Precision Engineering 37 (2013) 10–22

Contents lists available at SciVerse ScienceDirect

Precision Engineering

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

Evaluation of a servo settling algorithm

Brian A. Bucci [a], Jeffrey S. Vipperman [a,*], Daniel G. Cole [a], Stephen J. Ludwick [a,b]

[a] University of Pittsburgh, 636 Benedum Hall, 3700 O'Hara St., Pittsburgh, PA 15261, United States
[b] Aerotech Inc., 101 Zeta Drive, Pittsburgh, PA 15238, United States

ARTICLE INFO

Article history:
Received 6 September 2011
Received in revised form 1 April 2012
Accepted 16 April 2012
Available online 11 May 2012

Keywords:
Friction
Friction compensation
Point-to-point motion
Nonlinear control

ABSTRACT

The aim of this work is to discuss methods of friction identification and provide experimental evaluation of a novel control algorithm that enhances settling after point-to-point motion. This algorithm is called the Nonlinear Integral Action Settling Algorithm or NIASA. As the name suggests, the integral gain is nonlinear, and is based upon a Dahl friction model. The settling resulting from PID + NIASA control is nearly exponential, and governed by a time constant that is specified in the control design. As the NIASA algorithm requires, friction parameters must be identified for the servo under test. Two methods of friction identification (Step Tests and Identification Profile) are contrasted and found to provide comparable results, although the latter can provide advantages. The identified friction parameters are in turn used to perform four sets of control experiments; two PID controllers (standard factory tuning and high performance PID with acceleration feedforward) are tested both with and without NIASA compensation. In the case study with a factory tuned PID controller, servo settling times to within ±3–100 nm, are reduced by between 80.5% and 87.4% when NIASA compensation is added. When the NIASA compensator is added to the high performance PID controller, servo settling time is still reduced by between 50.5% and 73.0%. Although the NIASA compensator was designed to increase settling performance for relatively large point-to-point motions, similar positive results are achieved when the method is applied to smaller step motions that do not leave the pre-rolling friction regime. Frequency domain analyses demonstrated the nonlinear loop-gain of the plant, with a clear distinction between the rolling and pre-rolling friction cases. As expected, the nonlinear loop gain was found to lower the bandwidth for smaller motions. Adding NIASA control was observed to increase the bandwidth for small motions by a factor of 3–6, while having little effect for large motions.

1. Introduction

The behavior of the force of friction has long been known to cause problems in precision motion applications. In efforts to describe the issues caused by friction, advanced friction models, such as the Dahl model [1], LuGre model [2], and generalized Maxwell-slip model [3], have been developed. These advanced friction models are capable of reproducing the hysteretic behavior observed in real friction data [4].

This work aims to address the problem of reducing the time required to settle to nanometer level accuracy with a precision servo mechanism. While this work uses advanced hysteretic friction models, its direction is somewhat different from more widely accepted methods of friction compensation. Brief mention of these accepted methods of friction compensation will be made. However, the focus of this discussion is to state how such methods are appropriate for other motion control problems, but they are not appropriate for this particular problem.

One widely accepted method of friction compensation is friction model feedforward. With a known trajectory and model of the friction process, friction can be predicted and partially compensated by feedforward control [5]. In profile tracking applications, tracking performance can often be significantly improved [3,5–12]. In tracking applications, the position reference has dynamics which are passed through the friction model in attempt to cancel the force of friction. However, during settling, the servo's position reference is usually frozen to a static value. Therefore, feedforward friction compensation will have little to no effect on servo settling [5].

Another accepted method of friction compensation is the friction observer. Friction observers have been successfully implemented with most significant advanced friction models [2,5,11,13–18]. Several adaptive extensions have also been investigated [19–23]. In many previous efforts, friction observers are shown to improve servo tracking performance [2,5,14,15]. However, experimental results from some of these same authors suggest that friction observers may not improve servo point-to-point performance but rather, they may actually degrade it [11,13]. In their

* Corresponding author. Tel.: +1 412 624 1643; fax: +1 412 624 4846.
E-mail address: jsv@pitt.edu (J.S. Vipperman).

0141-6359/$ – see front matter
http://dx.doi.org/10.1016/j.precisioneng.2012.04.006

paper on an adaptive friction observer, Canudas de Wit and Lischinsky [13] go on to state that regular integral action is probably more useful for point-to-point motion than is the friction observer.

The most simple and practical way to achieve steady state error specifications is to include some controller integral action. The Yosida Nano-Mechanism Project presents the first case of a direct drive linear stage which is able to achieve nanometer precision with a single actuator [24,25]. This project represents a very similar situation that is being studied in the current effort. The key result from Futami et al. is that integral control was a major factor in achieving nanometer level positioning precision.

In previous work by the authors, an algorithm for settling servo mechanisms to nanometer level tolerances is proposed [26–28]. This method is called the Nonlinear Integral Action Settling Algorithm (NIASA). Some strengths of this method are its robustness to modeling errors in the friction process and how closely the proposed method relates to conventional PID tuning. In this work, the NIASA compensator will be briefly described. This will be followed by a discussion of how friction affects point-to-point motion. Next, parameterization of the NIASA compensator and friction model identification with be discussed. Then, the results of an example identification study and an actual point-to-point motion study will be presented. Finally, familiar frequency domain analysis will be used to describe the nonlinear controlled and uncontrolled systems at specific points of operation.

2. Control algorithm

This section is designed to briefly introduce the proposed NIASA control algorithm to the reader. For further description of the methodology used to design the NIASA algorithm the reader is referred to the references [27,28]. In a brief summary, the NIASA compensator is an extension of classical PID control, where the controller integral action is modified by a friction model. Integral action plays a key role in achieving nanometer level servo precision [24]. However, use of integral action can slow the response of the system and carries the risk of causing limit cycles [12,29,30]. Thus, this work aims to design the controller integral action to quickly achieve nanometer level precision, while avoiding undesirable characteristics.

The simplified equation of motion for a controlled servo, subject to friction, is

$$m\ddot{x} + F_r = u(t), \tag{1}$$

where m is the mass or moment of inertial, x is displacement, F_r is the friction process, and $u(t)$ is the control signal. PID control can be expressed as:

$$u(t) = k_P e + k_I \int_0^t e(t)dt + k_D \dot{e}, \tag{2}$$

where e is the position error and k_P, k_I, and k_D are the respective PID gains. For the servo mechanisms studied in this work the Dahl model has proved sufficient to describe the friction process. The Dahl model, in differential form, can be stated as:

$$\frac{dF_r}{dx} = \sigma \left(1 - \frac{F_r}{F_C} \mathrm{sgn}\dot{x}\right)^i, \tag{3}$$

where the differential dF_r/dx is the change in the value of the force of friction versus change in displacement, σ is the initial contact stiffness, F_C is the level of Coulomb friction, and i is a shape factor typically set to $i = 1$. Fig. 1 shows a graphical example of the behavior of the Dahl model. In Fig. 1 the simulated data starts at zero force on the left side of the plot. As the simulated system moves to the right, the force of friction increases and approaches the Coulomb level. When a velocity reversal occurs, at the upper right corner of the plot, a sharp transition in the force of friction is observed. As motion continues to the left, the force of friction approaches the opposing level of Coulomb friction. This pattern continues and the loops are traversed in the clockwise direction. The shape of each new transition curve that is initiated upon velocity reversal depends upon the friction state when the reversal occurs. Thus, the system has memory back to the last velocity reversal. Considering the behavior of the system described in Fig. 1, suppose the system starts at an arbitrary location with an arbitrary initial friction state. Suppose that it is desired to move the system to a second arbitrary location. The final friction state will depend on the initial friction state and the path to the desired location. Further, the final friction state could be a non-zero value. In this case, integral action is typically used to allow a servo under linear control to provide the necessary holding force to achieve zero steady state error.

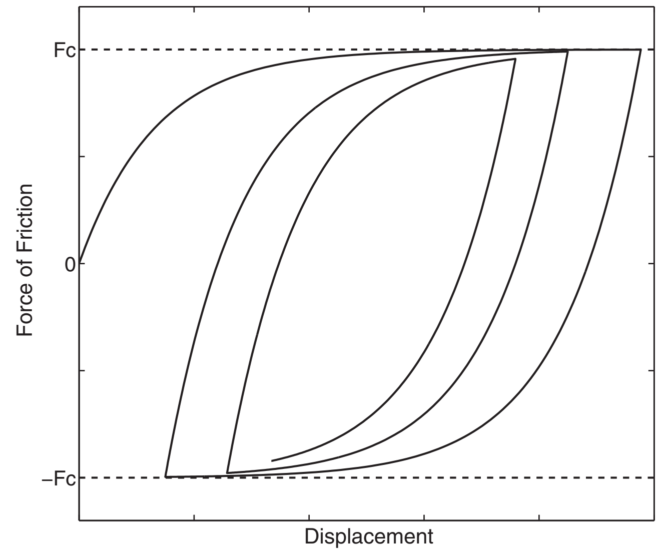

Fig. 1. Example of the type of response seen from Dahl's friction model to a decaying sinusoidal motion.

In Bucci et al. [27,28], the NIASA control law of

$$u(t) = \int_0^t \left(\frac{1}{\tau_d}\frac{d\hat{F}_r}{dx} + k_I\right) e(t)dt + k_P e + k_D \dot{e} \tag{4}$$

is proposed, where τ_d is a design time constant and $d\hat{F}_r/dx$ is the modeled differential of the friction process described by Eq. (3). The respective gains k_P, $k_I = k_P/\tau_d$, and k_D are the gains produced from the PID tuning.

The NIASA control law is designed to have an ideal closed loop response, governed by the design time constant, τ_d. Introducing the $d\hat{F}_r/dx$ term has the effect of linearizing the closed loop system. This additional nonlinear integral gain term will have a response similar to Fig. 1 after velocity reversal. Note that if we set $(d\hat{F}_r/dx) = 0$, the system reverts back to standard PID tuning, which is referred to as the "base PID" controller. Both the integral gain and the friction differential term are scaled by the reciprocal of τ_d.

Most simply described, this control law uses larger integral gains when very near to a velocity reversal, while traversing the steep part of the hysteresis curve. As the system moves further from velocity reversal the integral gain is reduced to maintain stability. The strength of this method is that it does not rely on an extremely accurate friction model or complex adaption. Conversely, a static parameterization, where parameters need only to be in the neighborhood of their true values, appears to offer significant improvement in point-to-point servo performance. The remaining sections of this document will focus on a brief discussion of how friction affects point-to-point servo motion, parameterizing