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Model-based controller design for machine tool direct feed drives

A.T. Elfizy, G.M. Bone *, M.A. Elbestawi

Department of Mechanical Engineering, McMaster Manufacturing Research Institute (MMRI), McMaster University, 1280 Main Street West, Room 316, Hamilton, Ont., Canada L8S 4L7

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Abstract

This paper presents a controller design methodology for machine tool direct feed drives. The methodology is applied to a linear motor (LM) and a piezoelectric actuator (PA). The structure of each plant model is obtained from physical laws and its parameters are obtained using system identification. A single transfer function (TF) model is shown to accurately predict the response of the LM. For the PA, multiple local models are required to accurately represent its dynamics. Next, a procedure for designing a model-based two degrees-of-freedom (2DOF) controller with anti-windup protection is presented for the single model and multiple model cases. With the LM, friction compensation, force ripple compensation and a disturbance observer are added to improve the tracking performance. Experimental results for both drives are included for step, ramp and sinusoidal reference inputs. For the LM, the rise time for a 1000 μm step input is reduced from 25 to 3.5 ms in comparison to a proportional-integral-derivative (PID) controller. For the PA, the rise time for a 10 μm step is reduced from 6 to 1.5 ms.

Keywords: Control systems; Input saturation; Linear motors; Machine tools; Piezoelectric actuators; System identification

1. Introduction

1.1. Direct feed drives

High-speed machine tool feed drive requirements are increasing in order to reduce both cutting and noncutting times, and improve productivity. These requirements include high acceleration, fast response and small tracking errors [1]. Ball screw feed drives are limited dynamically by their low first natural frequency. This represents a major drawback for high-speed systems, where the feed drive must respond to high frequency control signals. Linear motors (LMs) are a better solution for high-speed feed drives. They are capable of higher natural frequencies and have higher stiffness than ball screws because there is no elasticity involved [2]. Piezoelectric actuators (PAs) are increasing in importance in the field of micro-machining. PAs are able to provide high force (over 10 kN), and high stiffness (over 100 N/μm), motion with nano-scale resolution. However, they are limited by their low traveling distance [3].

1.2. Modeling nonlinearities and uncertainties

The direct contact between the moving mass and the actuator in both LMs and PAs causes the disturbances in the system to have a greater effect on positioning accuracy. Understanding these disturbances is crucial in designing a robust controller for direct drives. Force ripple in LMs can affect the accuracy and has to be pre-compensated in the controller design. Braembussche et al. [4] demonstrated a 75% improvement in tracking error when they utilized a controller for a linear synchronous motor consisting of feedback and feedforward components and force ripple compensation. VanBrussel and Braembussche [5] presented some drawbacks of LM drives, such as the increased sensitivity of the direct drive to load disturbances and the dependence of stiffness on the servo controller. They observed that load disturbances could result from varying mass of a workpiece, working position in case

* Corresponding author. Tel.: +1-905-525-9140x27591; fax: +1-905-572-7944.

E-mail address: gary@mcmaster.ca (G.M. Bone).

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