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Accurate Motion Control of XY High-Speed Linear Drives using Friction Model Feedforward and Cutting Forces Estimation

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Abstract

Accurate motion control is essential for machine tools. Both friction forces and cutting forces contribute to position and contour tracking errors. This paper presents a feedforward friction force compensation based on the Generalized Maxwell-slip friction model that describes friction behaviour both in pre-sliding and sliding regime. An inverse-model based disturbance observer is added to further improve the friction compensation. This disturbance observer is able to only partly reduce the effects of cutting forces. An almost complete elimination of these effects is obtained by adding a repetitive controller. Experimental validations of these approaches on a linear-motor based xy table are presented.

Keywords:

Accuracy, Control, Motion

1 INTRODUCTION

In machine tool direct drive applications, both friction forces and cutting forces from the machining process act directly on the motor and critically influence the tracking accuracy of a motion control system. Successful compensation of these acting disturbance forces is essential for accurate motion control.

Friction is a highly nonlinear phenomenon especially at velocity reversal. Quadrant glitches, characterized by spikes at quadrant locations during circular motion are a direct result of this highly nonlinear behaviour. As a result of the hard non-linear friction behaviour, friction can only be partly compensated using linear feedback control strategies such as PID, cascade P/PI or state-feedback control. More advanced techniques must be incorporated to achieve sufficiently high path and tracking accuracy.

Friction is categorized according to its pre-sliding and sliding regimes. Friction model-based feedforward of simple and more advanced friction models have been proposed in the literature. The simplest friction models consider friction in sliding regime only, which comprise a static map between friction force and velocity, e.g. viscous, Coulomb and Stribeck friction models. A more advanced friction model, the so-called Generalized Maxwell-slip (GMS) model, is a further improvement over the LuGre model as it describes the hysteresis non-local memory behaviour in pre-sliding regime [1].

The suppression of external disturbances acting on a motion control system is of equal importance. Various compensation methods have been proposed in literature. Repetitive control schemes were first introduced by Hara et al. [2] for tracking error compensation of periodic reference commands and disturbance inputs. Kempf et al. [3] present an inverse-model based disturbance observer to improve tracking performance against shock and vibration influence in a magnetic disk drive application. This approach can be applied to any disturbance and is effective up to a specified bandwidth which depends on the accuracy of the available system model. Literature on the application of these techniques for cutting force compensation is limited. Pritschow et al. [4] present a

cutting force estimator based on relative acceleration sensor measurements but do not report on the application of this estimator to effectively compensate the influence of these disturbances.

This paper discusses the design and experimental validation of friction and cutting force compensation for a linear drive xy table. The friction compensation consists of a GMS friction model based feedforward in combination with an inverse-model based disturbance observer. This disturbance observer is able to only partly reduce the effects of cutting forces. An almost complete elimination of these effects is obtained by adding a repetitive controller.

This paper is organized as follows. Section 2 discusses the experimental test setup. Section 3 gives a brief analysis of the cutting force characteristics. Section 4 presents the GMS friction model that is used in the friction feedforward compensation. Section 5 discusses the control structure and both friction and cutting forces compensation measures. Section 6 presents the experimental validation of these compensation methods.

2 EXPERIMENTAL SETUP

The test setup that is considered in this paper is a linear-drive based xy feed table of a high-speed milling machine (see Figure 1). The upper stage y-axis is driven by a single ETEL iron-core linear motor while the bottom stage x-axis is driven by two ETEL iron-core linear motors. Both axes are equipped with a 0.25 μ m resolution Heidenhain linear encoder. The stages run on Schneeberger preloaded roller guideways. In the absence of a velocity sensor, a velocity signal is calculated by means of numerical differentiation of the position in combination with a first-order low-pass filter. This filter is added to attenuate amplified measurement noise associated with the derivative action.

Figure 1: A xy feed table with three linear motors for high speed milling application.

The controller is implemented on a dSPACE 1103 DSP controller board linking the host computer to the ETEL drives. The dynamic coupling between both axes is negligible and the system dynamics can be described by two single-input single-output models. The models are obtained through frequency domain identification based on the measured frequency response functions shown in Figure 2.

Figure 2: FRFs measurements of x and y axes.

The identified models relate the control input voltage u to the table position z [m], with $z=x$ and $z=y$ for the x and y axes respectively, and are of second order with a time delay T_d .

$$G(s) = \frac{z(s)}{u(s)} = \frac{B}{s(s+A)} \cdot e^{-sT_d}, \quad (1)$$

with,

$A=28.57\text{volt/s}$, $B=4.526\text{m}$, $T_d=0.00065\text{s}$ for the x-axis;
 $A=20.00\text{volt/s}$, $B=8.916\text{m}$, $T_d=0.00065\text{s}$ for the y-axis.

These models do not include the resonance and anti-resonance frequencies above 40Hz shown in Figure 2.

3 CUTTING FORCES MEASUREMENT AND ANALYSIS

For experimental validation, an artificial cutting force is synthesized from an actual force measurement of a milling process; cutting of aluminium with an end mill of diameter 10mm at 1360rpm and 3mm depth of cut. It contains the first 15 harmonics of the measured signal. Figure 3 shows a comparison between the actual and the synthesized cutting force (left), and the spectrum of the synthesized signal (right).

Figure 3: Cutting forces and its spectrum analysis.

4 FRICTION MODEL

4.1 Generalized Maxwell Slip Model

The GMS friction model incorporates: (i) the Stribeck curve for constant velocity, (ii) hysteresis function with non-local memory for the pre-sliding regime, and (iii) frictional memory for the sliding regime. The model structure is similar to the Maxwell-slip structure, that is, it consists of a parallel connection of N different elementary slip-blocks and springs (see figure 4). Each block represents a generalized asperity of the contact surface that can either stick or slip and each element i has a common input, the position z , an elementary stiffness k_i , a state variable α_i that describes the element position, a maximum elementary Coulomb force W_i and a friction output F_i . A new state equation that characterizes sliding dynamics of each elementary slip-block replaces the original Coulomb law in the Maxwell-slip friction model structure.

Figure 4: Maxwell-slip friction with N-elementary models

The dynamic behaviour of an elementary slip-block during sticking, as the velocity v approaches zero, is described by a spring model with stiffness k_i :

$$\frac{dF_i}{dt} = k_i v \quad (2)$$

Slipping occurs if the elementary friction force F_i equals a maximum value $W_i = \alpha_i s(v)$. α_i is the normalized sustainable maximum friction force of each element during sticking and $s(v)$ is the Stribeck curve. The state equation describing the dynamic behaviour of an elementary slip-block is

$$\frac{dF_i}{dt} = \text{sign}(v) \cdot C \cdot \left(\alpha_i - \frac{F_i}{s(v)} \right) \quad (3)$$

The constant parameter C indicates the rate at which the friction force follows the Stribeck effect in sliding. The total friction force F is the summation of the output of all elementary state models and a viscous term σ (if viscous friction is present).

$$F(v) = \sum_{i=1}^N F_i(v) + \sigma \cdot v(t) \quad (4)$$

Friction compensation performance is validated from measured magnitude of the quadrant glitches that occur at near-zero velocity or at motion reversal, during circular tracking tests. Circular tests with 30mm radius at a constant tangential velocity of 100mm/s were performed. Figure 7 shows that adding GMS friction model feedforward in combination with the inverse-model based disturbance observer reduces the quadrant glitch magnitude from a maximum of 25 μ m to 3 μ m.

Figure 7: Measured circular tests and radial errors: (a) no friction compensation (b) GMS model feedforward and inverse model observer.

6.2 Cutting Force Compensation Performance

The synthesised cutting force, indicated in green in Figure 5, is applied to the input of both drives during a circular test. Figures 8 and 9 and Table 1 compare three different control configurations: (a) indicates circular test with GMS model feedforward only, (b) with added inverse-model based observer, and (c) with added inverse-model based observer and repetitive controller.

Figure 8: Circular test results and axial tracking errors.

The axial tracking errors and their spectrum analysis are summarized in Table 1 and Figure 9 respectively.

rms	(a)	(b)	(c)
x-axis	5.52 μm	3.62 μm	2.00 μm
y-axis	9.05 μm	3.88 μm	1.20 μm

Table 1: Root mean square of axial tracking errors.

Figure 9: Spectral analysis of tracking error along x-axis.

These results show the ability of the repetitive controller to effectively eliminate the first 8 harmonics of the cutting force. Higher harmonics have limited influence on the tracking error. The 8th harmonic (186 Hz) lies well above the bandwidth of the position controller (45 Hz) and of the inverse model disturbance observer (60 Hz). This is possible since the repetitive controller is only active in small frequency ranges around these harmonics and system phase lag is compensated for in its design [2,7]. The disturbance observer performance is limited by its bandwidth. A higher bandwidth is possible with a more accurate model, but will always be lower than the repetitive controller due to uncompensated system delay.

7 SUMMARY

This paper evaluates, experimentally, friction and cutting force compensation techniques on a linear drive xy-table. It is shown that friction feedforward compensation based on the advanced GMS friction model, in combination with an inverse-model based disturbance observer, can effectively reduce friction induced quadrant glitches. Due to its limited bandwidth, the inverse-model based disturbance observer is not able to compensate the cutting force higher harmonics. The developed high-order repetitive controller is able to totally compensate these harmonic disturbances far beyond the bandwidth of the position controller.

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