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Adaptive feedforward compensation of force ripples in linear motors

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Abstract

In this paper, an adaptive control scheme is proposed to reduce force ripple effects impeding motion accuracy in Permanent Magnet Linear Motors (PMLMs). The displacement periodicity of the force ripple is first obtained by using a Fast Fourier Transform (FFT) analysis. The control method is based on recursive least squares (RLS) identification of a nonlinear PMLM model which includes a model of the force ripple. Based on this model, the control algorithm can be commissioned which consists of a PID feedback control component, an adaptive feedforward component for compensation of the force ripple and another adaptive feedforward component based on the inverse dominant linear model which will serve to expedite motion tracking response. Simulation and experimental results are presented to verify the effectiveness of the proposed control scheme for high precision motion tracking applications.

Keywords: Permanent magnet linear motors (PMLMs); Force ripples; Fast Fourier Transform (FFT) analysis; Adaptive control

1. Introduction

In the real world, many applications require linear motion. Compared to the rotary motors, linear motors can be used to eliminate the mechanical coupling with accompanying of quietness and reliability. Nowadays, Permanent Magnet Linear Motors (PMLMs), as a specific type of linear motors, is receiving increased attention for use in applications requiring linear motion at high speed and high accuracy. In the realization of precision motion control in PMLMs, the presence of force ripples is a highly undesirable phenomenon which will degrade the achievable positioning accuracy. Fig. 1 shows the velocity–time response of a PMLM manufactured by Linear Drives Ltd (UK) for a constant input voltage signal. The presence of force ripples is self-evident and they are periodic with displacement along the motor. These ripples will yield problems in achieving a smooth and precise motion profile using only conventional feedback controllers, since the ripples will create "bumps" along the direction of motion.

Some effort has been devoted to suppress the force ripple. A force ripple model was developed and identified with a force sensor, and a feedforward compensation component was used to reduce force ripple (Braembussche et al., 1996). In (Otten et al., 1997) and (Hu et al., 1999), a neural-network-based learning feedforward controller was applied in the linear motor motion control system. In (Yao and Xu, 2000) and (Yao and Xu, 2002), an adaptive robust control scheme was proposed for the high speed and high accuracy motion control. Huang et al. (2002) presented a robust adaptive approach to compensate the friction and force ripple. In (Lee et al., 2000), the iterative learning control was applied.

The force ripple phenomenon has been described via a sinusoidal function of the position x (Otten et al., 1997). However, in reality, it is much more complex to model. The ripple can constitute the sum total of a number of

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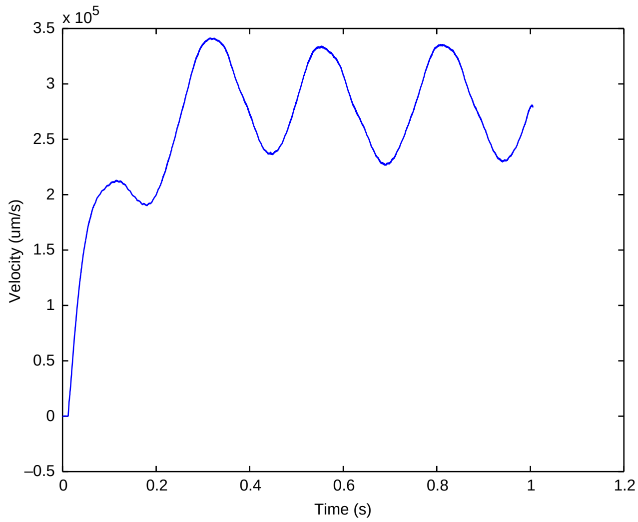

Fig. 1. Open-loop velocity–time response with input voltage of 0.8 V.

sinusoidal functions with unknown frequencies and amplitudes. In this paper, the displacement periodicity of the ripple is determined using a Fast Fourier Transform (FFT) analysis. However, in this case, the periodicity is with respect to displacement and not time. A displacement to time mapping is thus pre-performed in order to directly apply FFT in the usual way. With the spectrum available from the FFT analysis, the dominant frequency components can be extracted. Then, based on an inverse mapping, the displacement periodicity can be derived. Thus, we can build a more accurate model of the force ripples. With the displacement periodicity information available, a full model of the PMLM can be posed in the linear regression form to facilitate the application of the recursive least-squares estimation algorithm to identify the remaining model parameters. Based on the full model, the control algorithm can also be commissioned. It comprises of a PID feedback control component, an adaptive feedforward component which will compensate the force ripple, and another adaptive feedforward component based on the inverse dominant linear model, which will serve to speed up the motion tracking response. Simulation and experimental results will demonstrate the effectiveness and robustness of the proposed control scheme.

This paper is organized as follows. In Section 2, we first describe the model of the PMLM. In Section 3, a frequency analysis method is developed to derive the dominant displacement periodicity pertaining to the force ripple. In Section 4, the proposed overall control scheme is described, including the control configuration and the online estimation method used to identify the parameters. Finally, in Sections 5 and 6, the simulation and experimental results are furnished, respectively.

2. Modeling of the permanent magnet linear motor

In this section, a model of the PMLM with parameters specific to a LD series linear motor (LD 3810) will be presented. The motor components of an LD consist of the thrust rod, thrust block and robotic motor cable. The aluminum thrust block contains a series of cylindrical coils, forming the stator of the motor. The thrust rod contains high-energy permanent magnet pieces within a stainless-steel tube. For the system studied, a PWM amplifier with built-in electronic commutation is used to produce a force proportional to the control signal. A simplified model which combines the mechanical dynamics and the electrical dynamics is given in (Yao and Xu, 2002) and (Fujimoto and Kawamura, 1995):

$$u(t) = K_e\dot{x} + Ri(t) + L\,\mathrm{d}i(t)/\mathrm{d}t, \tag{1}$$

$$f(t) = K_f i(t), \tag{2}$$

$$f(t) = M\ddot{x}(t) + f_{ripple}(x), \tag{3}$$

where $u(t)$ and $i(t)$ are the time-varying motor terminal voltage and the armature current, respectively; $x(t)$ is the motor position; $f(t)$ represents the developed force; $f_{ripple}(x)$ denotes the ripple force. Other physical parameters are listed in Table 1 (Direct Thrust Linear Servo Motors & Systems, Linear Drives Limited, 1997).

Since the electrical time constant is much smaller than the mechanical one, the delay of electrical response can be ignored. At this time, the following equation can be obtained:

$$\ddot{x} = \left(-\frac{K_f K_e}{R}\,\dot{x} + \frac{K_f}{R}\,u(t) - f_{ripple}(x)\right)\Big/ M. \tag{4}$$

Let

$$a = \frac{K_f K_e}{RM}, \tag{5}$$

Table 1
Linear motor parameters

Motor	Units	LD 3810
Force constant (K_f)	N/A	130
Resistance (R)	Ω	16.8
Back EMF (K_e)	V/m/s	123
Length of travel	mm	2054
Moving mass (M)	kg	5.4
Armature inductance (L)	mH	17.4
Electrical time constant	ms	1.03
Peak force (F_p)	N	1300
Peak velocity	m/s	2.6
Peak acceleration	m/s^2	140
Continuous current	A	2.5
Continuous force	N	326
Continuous working voltage	V d.c.	320
Continuous working power	W	700