A High Speed, High Precision Linear Drive System for Manufacturing Automation

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Abstract - **High speed and high precision linear motions are found in many industrial applications, such as the wire-bonding and die-bonding of microelectronic components. In order to achieve the tight requirements of future-generation semiconductor packaging machines, a high-performance linear drive system is developed. The linear drive system consists of a Linear Permanent Magnet Synchronous Motors (LPMSM), and a DSP-based fully digital PWM drive. To achieve high trajectory accuracy, a dual-rate multi-loop cascade control structure with velocity and acceleration feed-forward is employed. Also, a velocity observer is used to provide reliable and ripple free feedback information. To increase the current dynamics, overrated momentary high-voltage and high-current are injected to the actuator's coils, through the PWM drive. Finally, to reduce mechanical resonance during the high-speed start-stop operations, a third-order profile generator is developed and employed in the motion path generation process.**

This paper describes the development of such a linear drive system. The paper includes (i) the construction and modeling of the Permanent Magnet Synchronous Linear Drive; (ii) the simulation of the linear drive and the control system; (iii) the design and hardware implementation of the linear drive system; and (iv) the implementation result. The final result shows that the system is capable of 5G acceleration and 1 micron position accuracy.

I. INTRODUCTION

Linear Permanent Magnet Synchronous Motors (LPMSM) has inherent advantages of direct drive, zero backlash, simple structure, high thrust density, and almost maintenance free [1, 2, 3]. Therefore it is particularly suitable for linear motion system where high speed & high precision are required. However, it has not gained widespread utilization, due to its non-conventional structure and the difficulty of direct-drive control [4, 5, 6]. Unlike rotary motors, LPMSM cannot operate and test under speed control mode; moreover, the motor has end-effects which needs to be considered and modeled. Under direct-drive mode, any disturbance in the load is directly reflected back to the PWM drive and the controller. Therefore, to operate the LPMSM at very high acceleration/deceleration rates and very high accuracy creates certain challenges to the drive designer.

This paper describes the structure of the LPMSM and its modeling method; the PWM drive and the current/motion controller; and the actual implementation of the drive system and its results.

II. CONSTRUCTION OF THE LINEAR MOTOR & DIGITAL DRIVE

Fig. 1 shows the structure of the LPMSM. It is a 3-phase permanent magnet synchronous motor with 3 separated Y-connected moving coils and a magnetic track as the stator.

Fig. 1. Direct Drive linear motion system

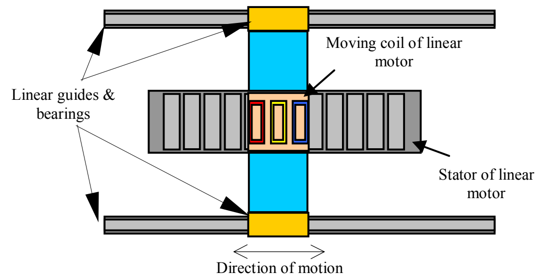

Fig. 2. Side view of the linear motor

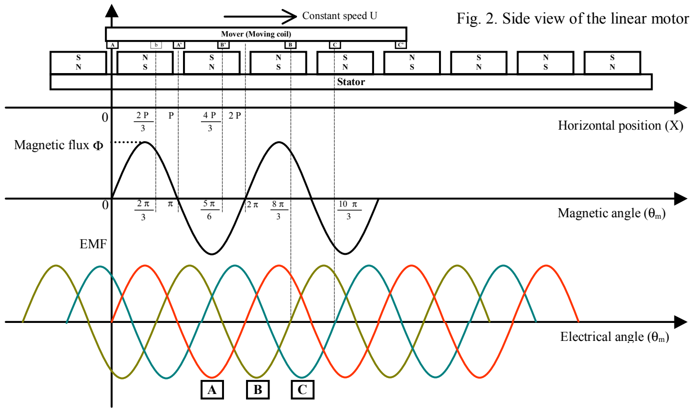

Fig. 2 is the simplified cross section of the linear motor. The magnetic flux density along the stator is designed to be a sinusoidal distributed. For the mover is moving in parallel over the stator in a constant velocity, the EMFs generated across the 3 coils are sinusoidal with 120° phase-shift from each other. The voltage equation for the LPMSM is thus given by EQT[1] below:

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$$\begin{bmatrix} v_a\\ v_b\\ v_c\end{bmatrix} = \begin{bmatrix} R&0&0\\0&R&0\\0&0&R\end{bmatrix}\begin{bmatrix} i_a\\i_b\\i_c\end{bmatrix} + \frac{d}{dt}\begin{bmatrix}L&0&0\\0&L&0\\0&0&L\end{bmatrix}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix} + K_e u \begin{bmatrix}\cos\left(\frac{ut}{p}\right)\\ \cos\left(\frac{ut}{p}-\frac{3\pi}{2}\right)\\ \cos\left(\frac{ut}{p}+\frac{3\pi}{2}\right)\end{bmatrix} \quad .....[1]$$

Where:

- L & R is the motor inductance and resistance respective
- v_a, v_b, v_c and i_a, i_b, i_c are respectively the voltages and currents of phase a, b & c.
- p is the pole pitch
- u is the linear velocity
- K_e is the back emf constant

Assuming that there is a complete electro-mechanical energy transfer, the thrust force produced by the motor is:

$$F_e = \frac{1}{u}(i_a e_a + i_b e_b + i_c e_c) \quad ....[2]$$

Taking into account the frictional force F_F , the mover's inertia M_M , the cogging force F_C and the load F_L, the mechanical force output is:

$$F_M = M_M \frac{d}{dt} u + B\,u + F_L + F_C \quad ....[3]$$

On the PWM driver side, the digital driver is modeled as SIMULINK blocks, as shown in figure 3 and 4.

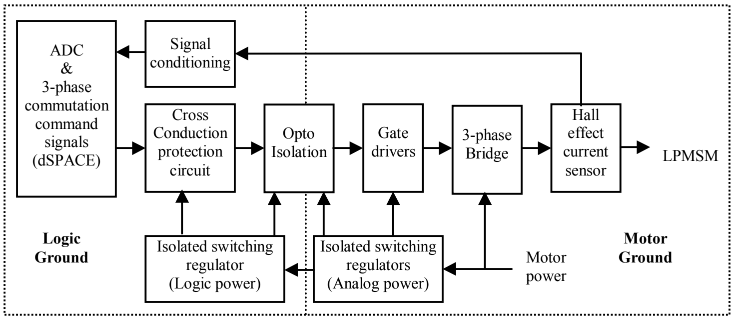


Fig. 3. Block diagram of the digital driver

The block diagram of the digital driver is as shown in Fig. 3. It consists of a PC and a DS1102 dSPACE card serves as the current controller. The Hall-effect current sensors signal condition circuit, IGBT power switch and the gate driver are on the wire-wrap board. The Matlab model of the driver is shown in Fig. 4.

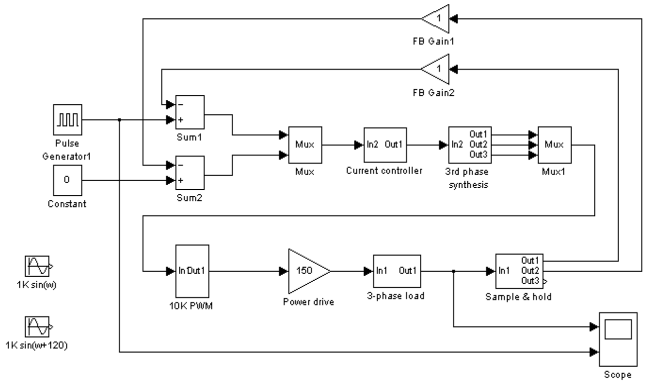


Fig. 4. MatLab model of the digital driver

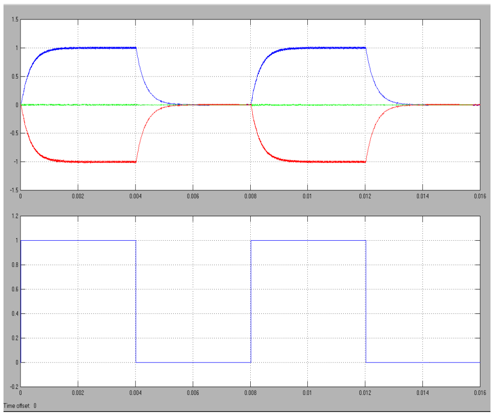


Fig. 5. Simulated current response of the power driver

Fig. 5 shows the simulated response of the digital current driver with 125Hz step input. The result shows that the current can track the command (1A) quite well, and there is no instability in the current profile.

III THRUST CONTROL OF THE LINEAR MOTOR

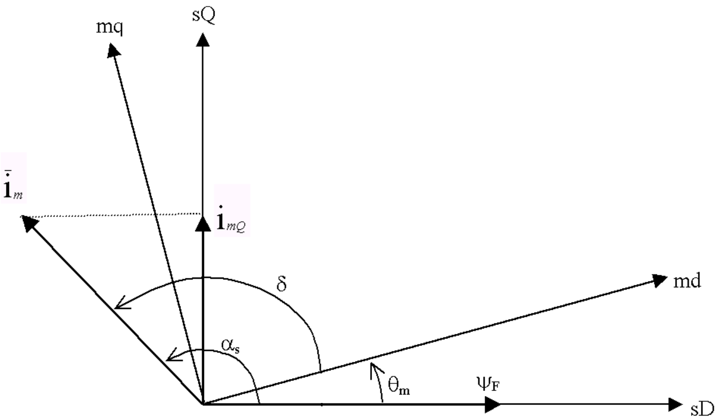


Fig. 6. Space vector diagram of the LPMSM

As shown in Fig. 6, the thrust force of the LPMSM is the cross-product of the space vector of the stator magnet flux ($\bar{\psi}_F$) and the space vector of the mover current. ($\bar{I}_m$). The thrust force can be written as:

$$T_F = C_F \;\bar{\psi}_F \times \;\bar{i}_m$$

Where C_F is a constant

$\bar{\psi}_F$ is the flux linkage space vector in stator reference frame

$\bar{i}_m$ is the mover current space vector in stator reference frame

It is therefore the i_{mQ} component of the current space vector of the mover has the effect of producing the magnetic force, and the thrust force is thus:

$$T_F = C_F\, \psi_F\, i_{mQ}$$

or

$$= C_F\, \psi_F\, |\,\bar{i}_m| \sin\alpha_S$$

So maximum thrust can be obtained when the mover current space vector is 90° advance the direct axis of the stator magnet flux. The magnetic position of the mover with respect to the stator is monitor by the linear encoder.

Fig. 7 below is the block diagram for the thrust control of the LPMSM.

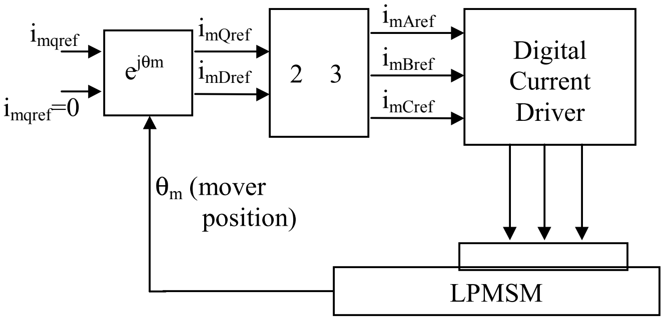


Fig. 7. Thrust Control of the LPMSM

A linear incremental encoder is used to monitor the mover position. The mover current components in the stationary reference frame (i_{mQref} & i_{mQref}) are obtained by using the transformation exp(jθ_m). The actual 3-phase current command for the digital driver is obtained by the application of the 2-phase-to-3-phase transformation [11]. Below is the matrix for the 2-phase-to-3-phase transformation:

$$\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \begin{bmatrix} \cos\theta_m & \sin\theta_m & 1 \\ \cos(\theta_m - 2/3\pi) & \sin(\theta_m - 2/3\pi) & 1 \\ \cos(\theta_m - 4/3\pi) & \sin(\theta_m - 4/3\pi) & 1 \end{bmatrix} \begin{bmatrix} S_q \\ S_d \\ S_0 \end{bmatrix} \quad ...[4]$$

Where θ_m is the mover electrical angle and is equal to ut/p

IV MODELLING OF THE LINEAR DRIVE SYSTEM

Fig. 8 shows the proposed control strategy for the linear drive system. It is a dual-rate multi-loop cascade control structure with velocity and acceleration feedforward is employed. Also, a velocity observer [7] is used to provide reliable and ripple free feedback information

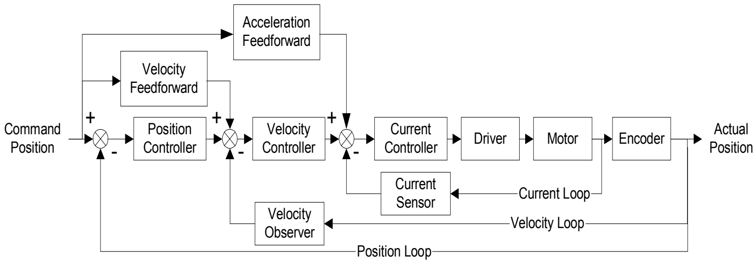


Fig. 8. Block diagram of the control system of the LPMSM

The simulated response of the position control for a travel of 60K encoder counts (60mm) is shown in Fig. 9.

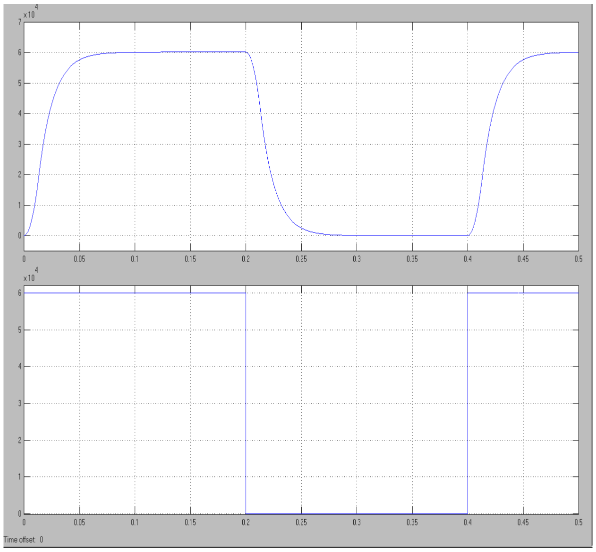


Fig. 9. Simulated response of the Trajectory Controller

V HARDWARE IMPLEMENTATION OF THE LINEAR DRIVE SYSTEM

Fig. 10 and Fig. 11 are the construction of the LPMSM and the power driver of the LPMSM system. Since all the current and trajectory control functions are implemented digitally, the overall hardware is not very complicated.

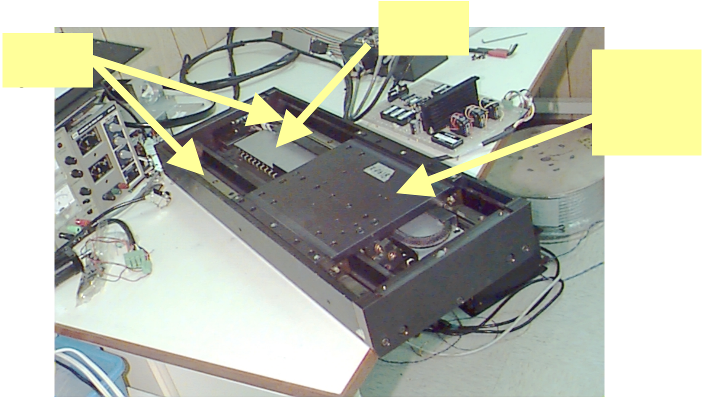
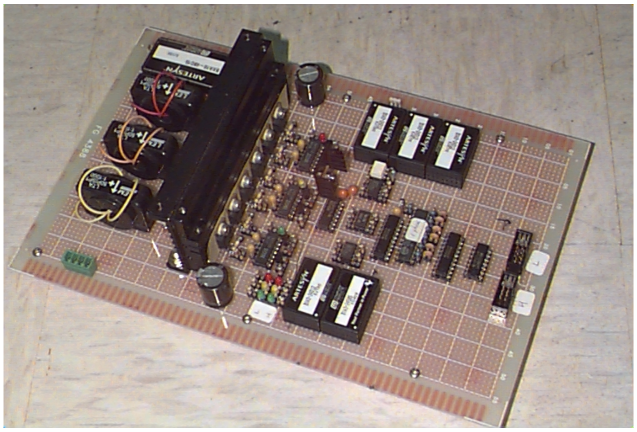


Fig. 10. LPMSM construction



V RESULT OF HARDWARE IMPLEMENTATION

The actual current step responses of two of the phases of the LPMSM driver are shown in Fig. 12 and Fig.13. These results show that the current profile can track the command current closely.

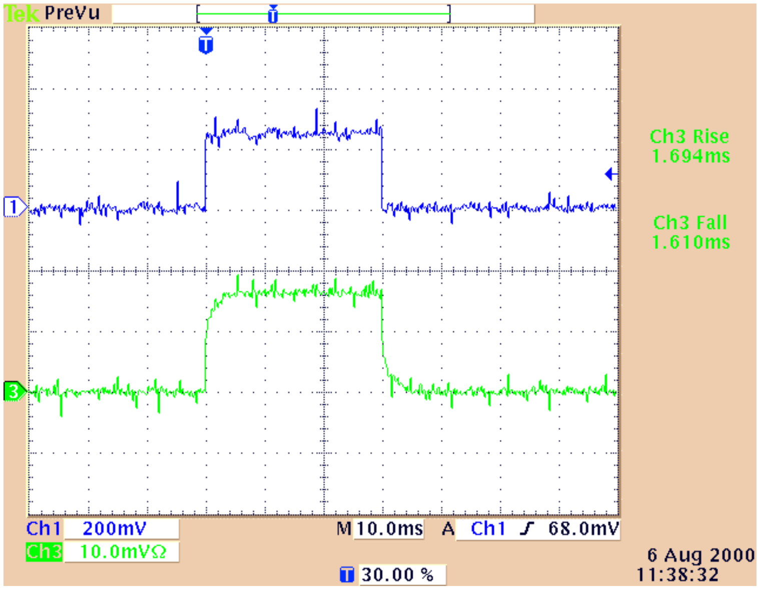


Fig. 12. Phase A current loop response

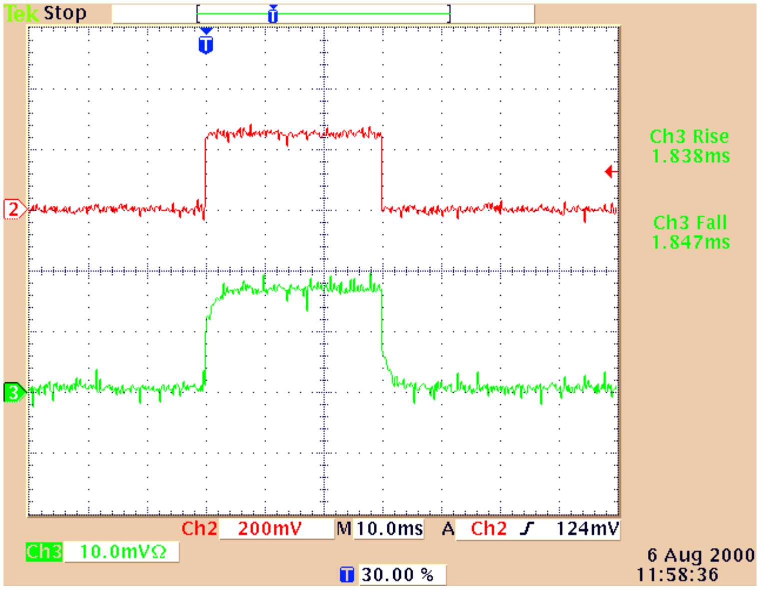


Fig. 13. Phase B current loop response

The response of the position loop is shown in the Fig.14, Fig. 15, Fig. 16 and Fig. 17. Sampling frequency for the current loop and position loop is 10KHz and 2KHz respectively. A third order profile is used to generate the position command signal for a better position tracking and minimize the stress on the current driver and the motor.

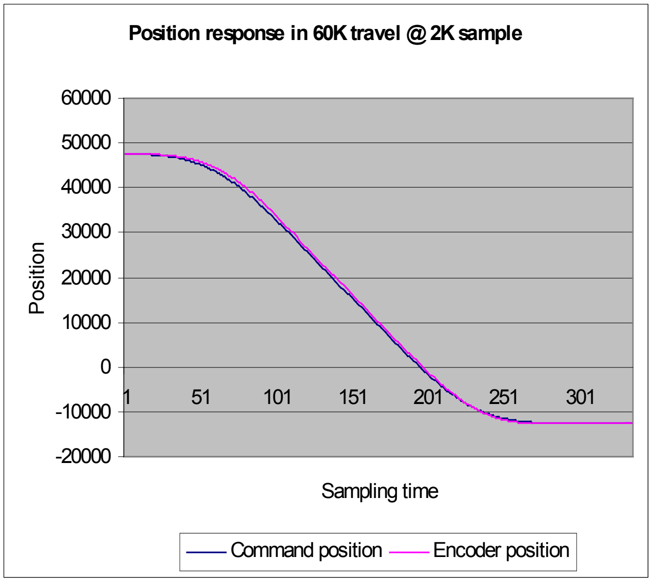


Fig. 14. 60mm point-to-point travel using a third order profile

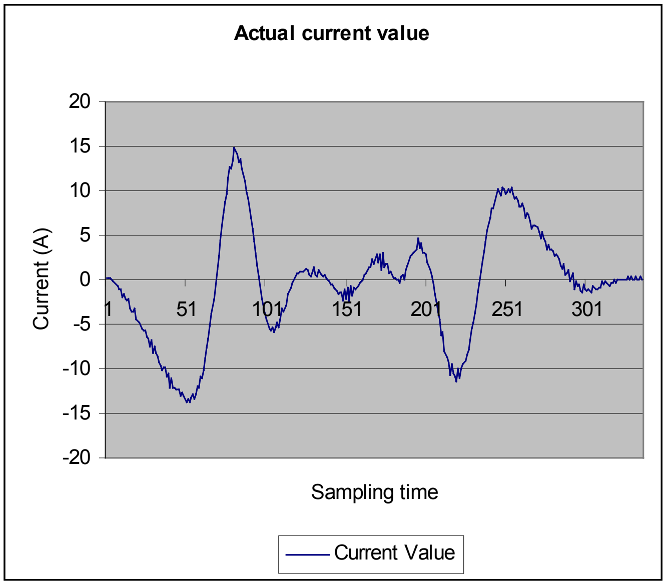


Fig. 15. Actual current waveform for the 60mm travel

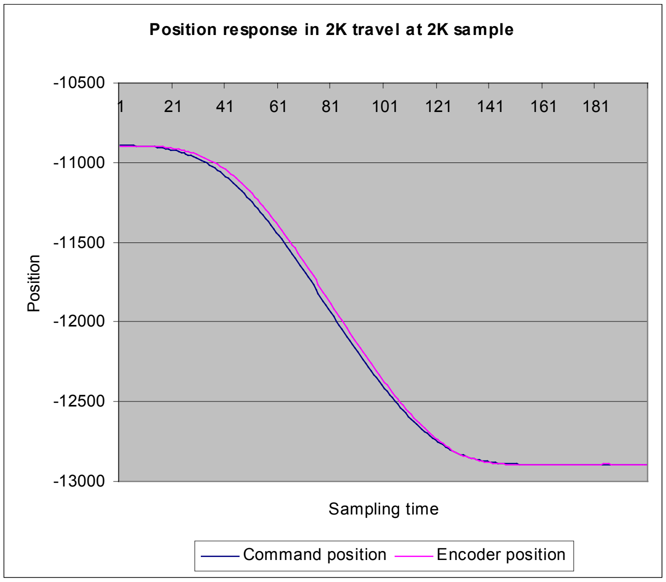


Fig. 16. 2mm point-to-point travel using a third order profile

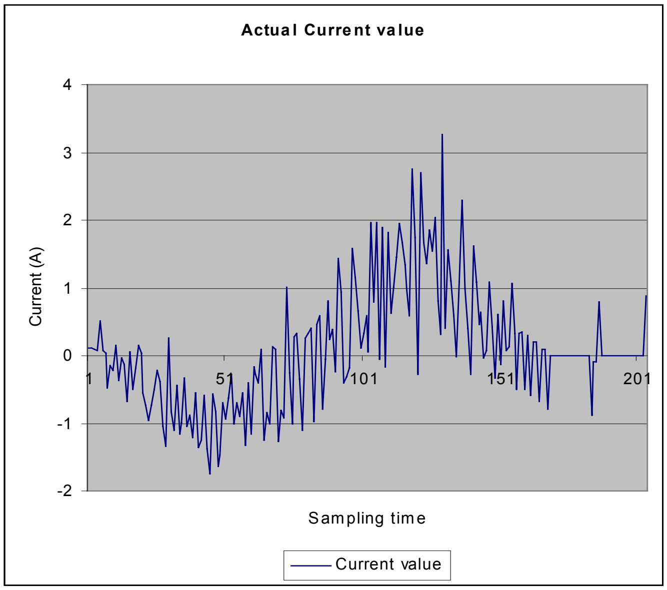


Fig. 17. Actual current waveform for the 2mm travel

VII CONCLUSION

This paper describes the development of a linear drive system with high-acceleration/deceleration and high accuracy performances. A fully digital PWM circuit that supplies momentary over-rated current to the LPMSM is constructed. A dual rate multi-loop cascade controller with velocity/acceleration feedforward and velocity observer is proposed. The overall system is simulated and implemented in hardware. Both simulated results and implementation measurements show that the current controller has a fast current loop response and good current tracking ability. The current loop has bandwidth of 1.5KHz and a driving capacity of 25A peak current at 150Vdc. The digital current driver exhibits very low temperature-drift (20mA max.) and offset-drift (5mA max.). The system has the ability to drive the linear motor at a speed of 4m/s, a peak acceleration of 5G, and a position error of 1 micron. The developed linear drive system is very suitable for deployment in next-generation of high-performance electronic packaging machines.

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