# 외부회로가 결합된 선형 BLDC 전동기의 유한요소법을 이용한 동특성 해석

論 文
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# Dynamic Characteristics Analysis of Linear BLDC motor using Finite Element Method Coupling with External Circuit Model

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Abstract - This paper presents the dynamic characteristics of a linear brushless dc (BLDC) motor with permanent magnet excitation for the precision conveyor according to the load condition. Dynamic performance of the linear BLDC motor driven with 6 step inverter such as thrust force and speed is simulated by finite element method coupling with external circuit and measured for the prototype motor. The results of finite element analysis are compared to the experimental results and verify reliability.

Key Words : Dynamic characteristics, Load condition, Coupling analysis, Linear BLDC motor

## 1. Introduction

Compared with rotary motors, linear motors possess many advantages in linear motion driving applications, such as direct driving, low frictional loss, high position control accuracy, high speed, high acceleration and deceleration capability, large structural flexibility, high reliability etc. The linear brushless DC motor (LBDCM) is basically a permanent-magnet linear synchronous motor with moving-member position sensing. Owing to its advantages such as high power density, high force-mass ratio and ease of control it has been widely employed in factory and office automation equipment [1-2].

The linear BLDC motor has less backrush and friction, so it can be used as a part of microprocessors and power electronics. Therefore, the linear BLDC motor can broaden its usage in areas such as the wafer stepper stage in the semiconductor industry [3].

The predominant nonlinear effects of the linear BLDC motor systems are the force ripple. In order to reduce the effects of the force ripple of the linear BLDC motor, it is necessary to analyze the dynamic characteristics according to its control method and the load condition [3].

This paper deals with the dynamic characteristics of the linear BLDC motor for future application in the semiconductor industry, where incremental precision control is absolutely needed. An equivalent magnetic circuit model is derived to calculate thrust at the design state. For the prototype linear BLDC motor, parameters for the dynamic characteristic such as speed and thrust are calculated and compared with those from measurements and finite element analysis (FEA) at the design stage.

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## 2. Analysis Model and Magnetic Circuit Modeling

### 2.1 Analysis model

The linear BLDC motor considered in this paper consists of stator and mover. Permanent magnets are mounted on the stator and three phase windings are wound at mover as shown in Fig. 1. Fig. 1 (b) shows the cross-sectional view.

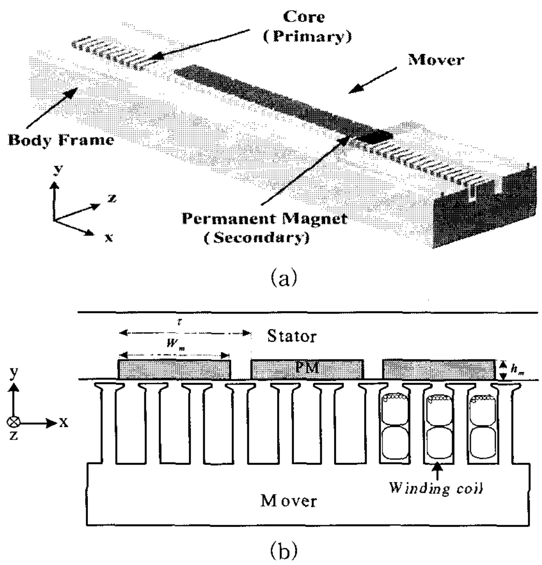



Fig. 1 Analysis model (a) Three-dimensional structure of the linear BLDC motor (b) Cross-sectional view.

### 2.2 Magnetic Circuit Modeling

The inverter fed linear BLDC motor system is modeled by a finite element analysis to determine the parameters using an analog circuit. The finite element analysis region of the motor is the checked region as shown Fig. 2. The parameters changed with the variation of load conditions and the results feed back into the solution progresses. In order to estimate the dynamic characteristics of this linear machine system, the circuit equations for a finite element model must be used. (1), (2) and (3) are the governing equation, the circuit equation and the force equation, respectively. Table I shows the specifications of the linear BLDC motor.

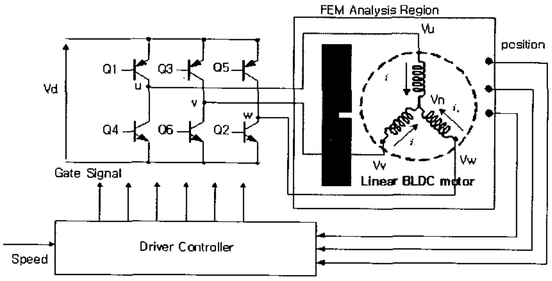



Fig. 2 Electrical scheme for the linear BLDC motor

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=-\frac{N}{S}I_u-\frac{N}{S}I_v-\frac{N}{S}I_w -\frac{1}{\mu}\left(\frac{\partial M_y}{\partial x}-\frac{\partial M_x}{\partial y}\right)+\sigma'\left(\frac{\partial A}{\partial t}+\nabla\phi\right) \quad (1)$$

where $\mu$ stands for permeability, $N$ for coil turns, $S$ for the cross section area of the winding with a phase current $I$ and $M$ for magnetization of permanent magnet. Also subscripts u, v and w represent each phase.

$$\frac{d\Phi_y}{dt}-\frac{d\Phi_w}{dt}+L_0\frac{dI_y}{dt}+L_0\frac{dI_w}{dt}+R_uI_u-R_wI_w=V_u-V_w$$
$$\frac{d\Phi_y}{dt}-\frac{d\Phi_v}{dt}+L_0\frac{dI_y}{dt}+L_0\frac{dI_v}{dt}+R_uI_u-R_vI_v=V_u-V_v \quad (2)$$

where $\Phi$ is the flux linkage of phase winding, $I$ is the phase current and $V$ is the phase voltage.

$$F_e=m\frac{d^2x}{dt}+B\frac{dx}{dt}+F_L \quad (3)$$

where $F_e$ is the electrical thrust, $m$ is the total mass of the moving element system, $x$ is the position of the mover, $B$ is the viscous friction and iron-loss coefficient, $F_L$ is the external load thrust.

Eq. (1) and flux linkage $\Phi$ in eq. (2) can be obtained by finite element method.

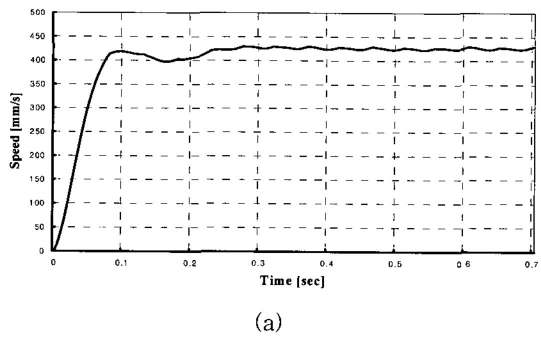
Table 1 Specification of induction motor

| | | |
|---|---|---|
| Stator (Primary) | Pole pitch | 60[mm] |
| | Slot pitch | 20[mm] |
| | Slot width | 13[mm] |
| | Rated current | 5.4[A] |
| | Slot/pole/phase | 3 |
| | Conductor length | 55[mm] |
| Mover (PM) | Height | 10[mm] |
| | Width | 50[mm] |
| | Material | Rare earth Nd-Fe-B |
| | Residual induction | 1.25[T] |
| | Mechanical air-gap | 10[mm] |

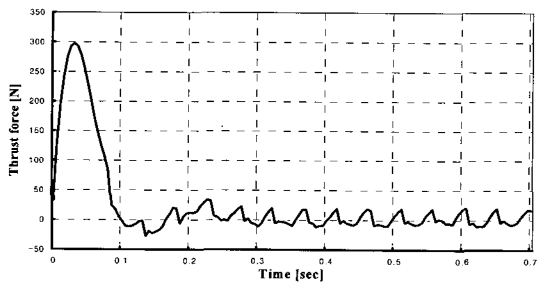
## 3. Analysis results and comparison

### 3.1 Electromagnetic characteristics

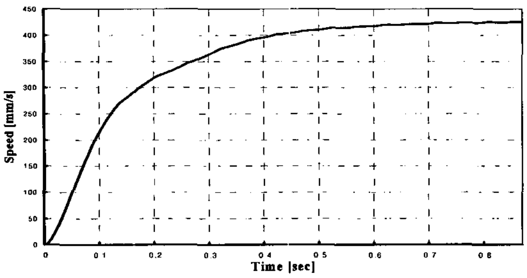
Fig. 3 shows dynamic characteristics; the speed and thrust curves of linear BLDC motor. Fig. 3 (a) and (b) show under no-load condition, Fig. 3 (c) and (d) show under load condition. As seen in these figures, the speed rising time is different according to load condition. Rated speed gets to static state at 0.25[sec] with no-load, the other side, rated speed of load condition gets to static state at 0.6[sec]. The thrust is increased when motor is loaded.



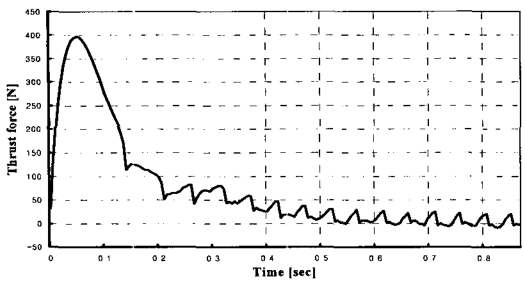

(a)




(b)



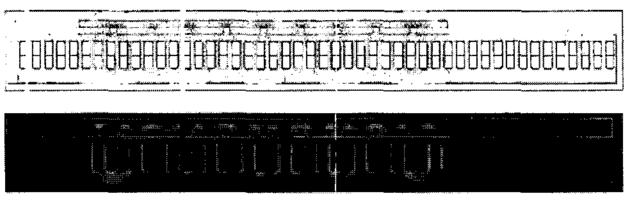

(c)



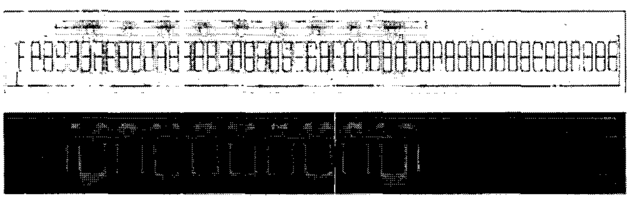

(d)

Fig. 3 Dynamic characteristics of linear BLDC motor without load and with load(1000[N]) (a) Speed without load (b) Thrust without load (c) Speed with load (d) Thrust with load

Fig. 4 and Fig. 5 show the flux plots of the linear BLDC motor on two different time points under no-load condition and load condition, respectively. And Fig. 4 shows the instantaneous flux at 0.1 [sec], both (a) and (b) the mover started at the left origin point, and it can be seen that the mover moves farther under no-load condition. Fig. 5 shows the steady state at 0.6 [sec] and has the similar results of Fig. 4. But Fig. 4 is in the instantaneous state the exciting current is large, so the flux density is also large.

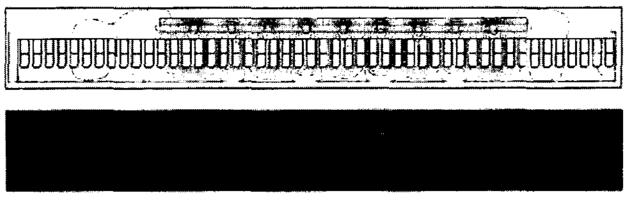


(a)

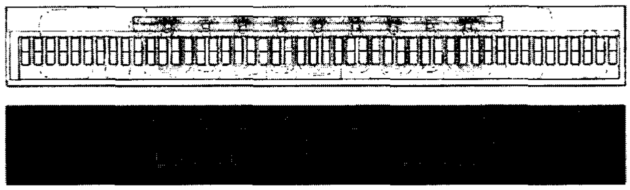


(b)

Fig. 4 Flux plots without load and with load (1000[N]) at starting region (a) Displacement at 0.1[sec]-without load (b) Displacement at 0.1[sec]-with load



(a)



(b)

Fig. 4 Flux plots without load and with load(1000[N]) at steady running region (a) Displacement at 0. 6[sec]-without load (b) Displacement at 0.6[sec]-with load

### 3.2 Comparison to Experimental Results

Fig. 6 shows photos of the prototype Linear BLDC motor. The three phase coils sit on the mover and the stator has an Nd-Fe-B permanent magnet on the base side. This motor has a pole pitch of 60mm and air gap 10mm. In the characteristics test, the input voltage is generated by the three phases - two exciter using PWM inverter and the position of mover is detected through hall sensor.

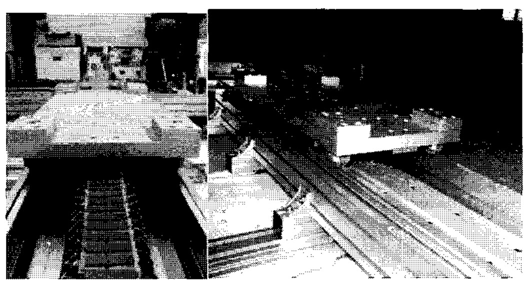
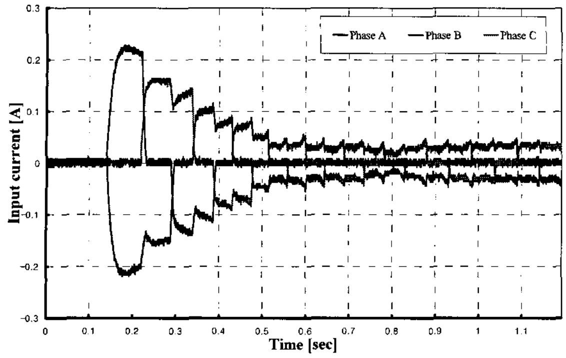


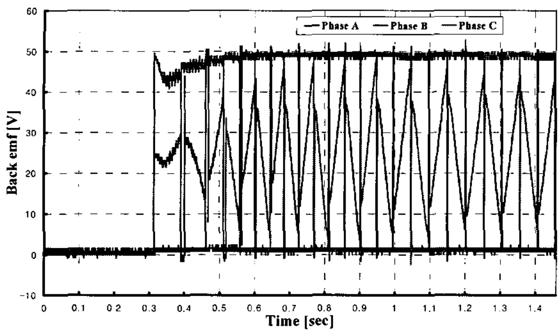
Fig. 6 Prototype photos of linear BLDC motor

Fig. 7 and Fig. 8 show the experimental results of phase current, back EMF, speed and thrust of linear BLDC motor under no-load and load condition. The current waves have distortion because flux density distribution of coils closes to sinusoidal wave. Back EMF is increasing until speed is reached to static state. The experimental speed and thrust curves are similar to the simulation results.

Fig. 9 shows the comparison of simulation and experimental results of cogging force. The cogging force is caused by the interaction of the permanent magnet and the iron core, and the end effect. The validity of analysis results was also verified by comparing the analyzed results with the measured ones.




(a)

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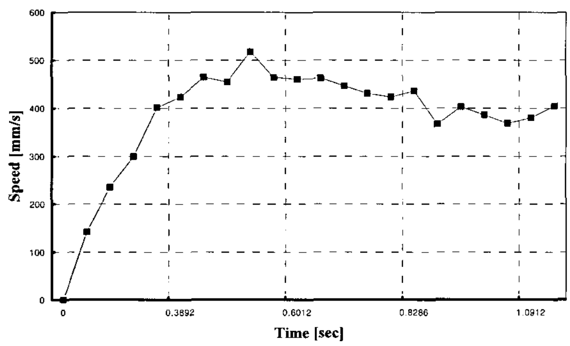


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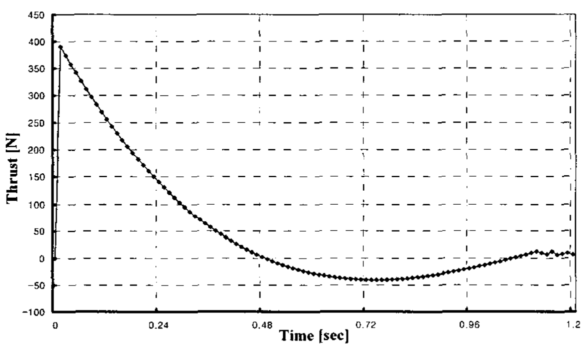
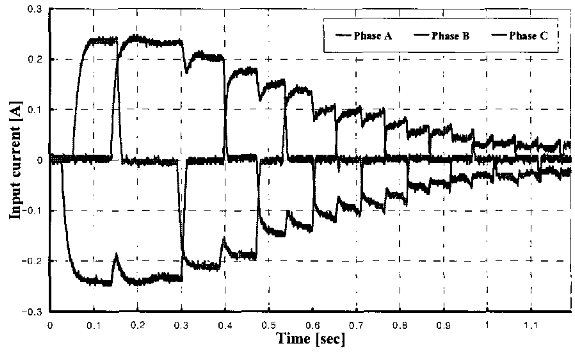
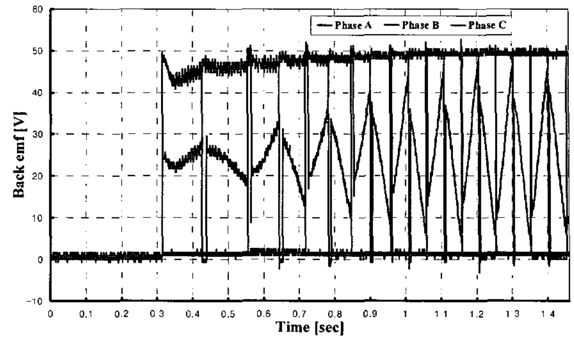



(d)

Fig. 7 Dynamic characteristics of linear BLDC motor with no-load (a) Phase current (b) Speed (c) Back EMF (d) Thrust




(a)

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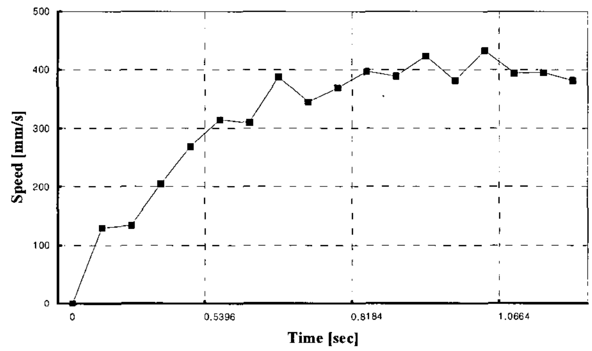


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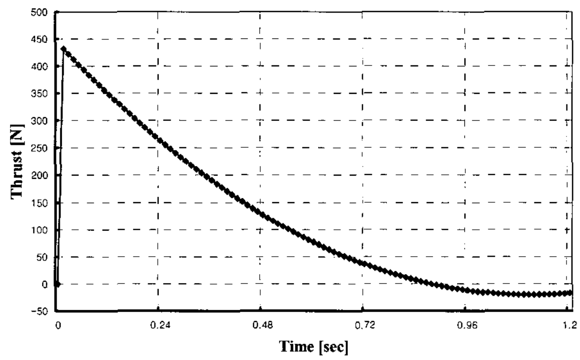


(d)

Fig. 8 Dynamic characteristics of linear BLDC motor with load (1000[N]) (a) Phase current (b) Speed (c) Back EMF (d) Thrust

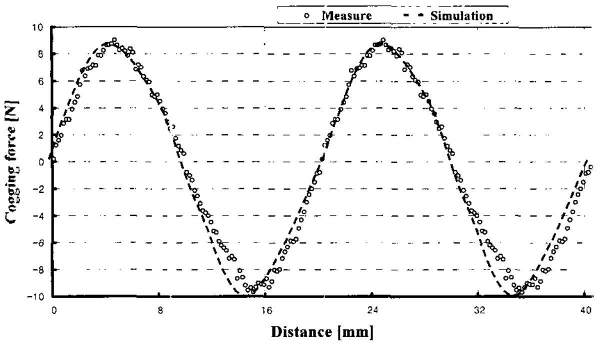


Fig. 9 Comparison of simulation and experimental results of cogging force

## 5. Conclusion

In this paper, to analyze the accurate dynamic performance of 6 step inverter-fed linear BLDC motor according to the load condition, finite element techniques coupling with external circuit models, together with the simultaneous simulation of motion of the mover system, are proposed. From the results, it is shown that the simulation results and the experimental results are similar, so this proposed method is suitable. And the validity of analysis results was also verified by comparing the analyzed results with the measured ones.

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