2000년도 대한전기학회 하계학술대회 논문집 2000.7.17-20

전자석형 리니어 하이브리드모터의 과도특성 해석

전 혜정*, 전 우진**, 이 주**, 카미야 유우시***
*LG종합기술원, **한양대학교, ***국립군마대학교(일본)

Transient Characteristics of Electromagnet Type Linear Hybrid Motor

Hyejeong Jeon*, Woojin Jeon**, Ju Lee**, and Yushi Kamiya***
*LG Electronics Institute of Technology, **Hanyang University, ***Gunma Nat'l University in Japan

Abstract - This paper treats the electromagnet type linear synchronous motor with induction operation. The proposed motor consists of the primary winding energized by variable frequency supplies and the secondary having an additional solid-conductor besides the field winding. The conductor is useful for not only the self-starting but also the damping effect in the synchronous drive. From the investigation by the experiment and the finite element analysis coupled with both electric circuit and motion equation, we verify that the proposed motor is effective for practical use.

1. INTRODUCTION

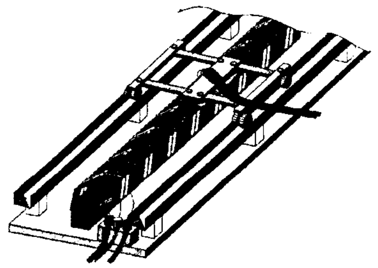
While the performance of the linear induction motor (LIM) is superior to that of linear synchronous motor (LSM) in the starting process, the former motor is inferior to the latter one in the efficiency and power factor. The starting behavior of LSM generally depends on the ramp input of supply frequency or the induction operation of damper winding [1], [2]. In this paper, we propose a novel hybrid drive by using both LIM and LSM actions.

The LSM of our research consists of the long primary energized by two stages of supply frequencies and the short secondary having both field winding and solid-conductor. The high-frequency supply for starting and the low-frequency supply for synchronous drive excite the primary winding. By applying higher supply frequency to the starting, the motor is capable of producing three kinds of thrusts (i.e., the starting one by 50[Hz], the synchronous and the damping ones by 10[Hz]). The reason for using the induction-motor action at starting is that it can accelerate the secondary more quickly and stable than that of LSM alone.

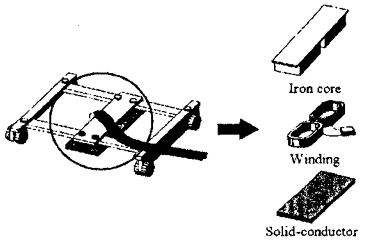
We first investigate the performance of the proposed motor by the finite element method (FEM) and the experiment. To obtain the dynamic and transient characteristics, we couple the method with both electric circuit and motion equation. Then, we derive an optimal feeding condition to the varying load concerned. Finally, we confirm that the proposed motor is effective for practical use in view of both high acceleration and convergence of hunting oscillations.

2. STRUCTURE & PRINCIPLE

Figure 1 shows the structure of our proposed motor, table 1 the experimental specifications, and table 2 the investigated secondary types. In the figure, the secondary consists of the electromagnet made of iron-core and field winding, and an additional solid-conductor of copper. The field winding is excited by direct current (d.c.) after the secondary reaches to the synchronous speed.



(a) Overview of experimental machine



(b) Secondary construction

Fig. 1. Structure of the proposed motor.

Table 1. Experimental specifications

Symbol	Quantity	Value [Unit]
τ	Length of pole pitch	0.084 [m]
W_p	Width of primary-core	0.028 [m]
W_t	Width of tooth	0.007 [m]
W_s	Width of slot	0.007 [m]
N_p	Number of turn (primary winding)	50 [turns]
N_s	(field winding)	80 [turns]
L_s	Length of secondary	0.168 [m]
d_s	Thickness of secondary conductor	0.0015 [m]
M_s	Weight of secondary	1.1893 [kg]
I_{pi}	Primary current (in induction drive)	1.5 [A]
I_{ps}	(in synchronous drive)	2.7 [A]
I_s	Secondary current	2.0 [A]
f_i	Frequency (in induction drive)	50 [Hz]
f_s	(in synchronous drive)	10 [Hz]
g	Length of air-gap	0.005 [m]

Table 2. Classification of the secondary

Type	Secondary conductor	Field winding
Type A	Existence	Short
Type B	Existence	Open
Type C	Non-existence	Short

To examine the effective hybrid drive by both induction and synchronous operations, we supply the high-frequency source of 50[Hz] at starting and the low-frequency one of 10[Hz] at synchronous drive, as shown in Fig. 2.

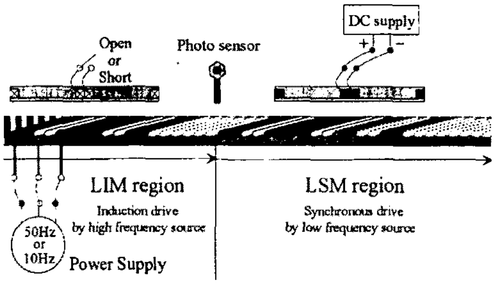


Fig.2. Experimental apparatus for hybrid drive.

3. ANALYSIS METHOD

To obtain the transient characteristics of the motor, we couple the finite element analysis with both electric circuit and motion equation [3], [4]. Two-dimensional magnetic fields can be expressed as,

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial \mathbf{A}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial \mathbf{A}}{\partial y}\right)=-\left(\mathbf{J}_0-\sigma\frac{\partial \mathbf{A}}{\partial t}\right) \tag{1}$$

where A, σ, J_0, μ denote the magnetic vector potential, the conductivity, the magnetizing current density, and the magnetic permeability, respectively. And the circuit equation for field winding is governed by,

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t}+L_s\frac{\mathrm{d}i_s}{\mathrm{d}t}+R_s i_s=0 \tag{2}$$

where Φ, L, and R are the linkage flux of coils, the leakage inductance of the coil ends, and the resistance of the coils, respectively. Since the currents are related to the magnetizing current density and the linkage flux to the magnetic vector potential, the interface conditions for coupling the magnetic field equation and the electric circuit equation are,

$$i=\mathbf{J}_0 S_c$$
$$\Phi=N\iint_S \mathbf{B}\cdot \mathrm{d}S_l=N\oint_l \mathbf{A}\cdot \mathrm{d}l \tag{3}$$

where S_c, S_l mean cross-section of a coil conductor and area of a coil loop, respectively. Combining (1) with (2) and (3), the unknown vector potential and the secondary current can be calculated [5]. The motion equation to express the secondary movement is given by,

$$M\frac{\mathrm{d}^2x}{\mathrm{d}t^2}+k\frac{\mathrm{d}x}{\mathrm{d}t}+\mu_f\left(Mg-F_z\right)=F_x \tag{4}$$

where M, k, and μ_f are the secondary mass, the coefficient of viscosity, and the coefficient of friction, respectively.

4. RESULTS

4.1 Static Characteristics

Since the secondary construction is considered three types as shown in table 2, we first investigate the induction and synchronous characteristics of the motor in each type. Figure 3 shows the thrust versus slip and Fig. 4 the velocity versus time. In the figures, the proposed motor starts by high frequency source of f=50[Hz]. In spite of the additional secondary winding, the results indicate that *Type A* is inferior to *Type B* because of its end effects and larger leakage reactance.

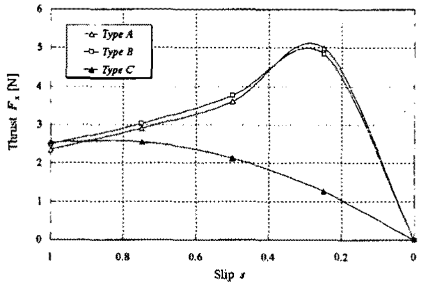


Fig. 3. Thrust versus slip (Analysis).

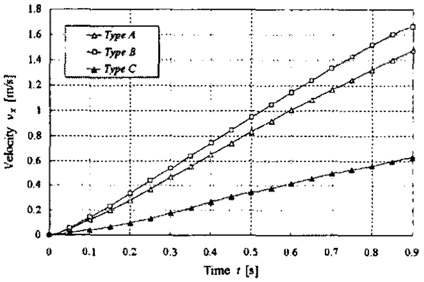


Fig. 4. Velocity versus time (Experiment).

When the field winding is energized by d.c. supply, the motor produces the synchronous thrust by the relative position between the primary and secondary poles. Figure 5 shows the thrust versus power angle and Fig. 6 the damping thrust versus slip near the synchronous speed. From the figures, we can recognize that the maximum value of the synchronous thrust inclines to the center of secondary because of the saliency, and *Type B* provides largest damping thrust.

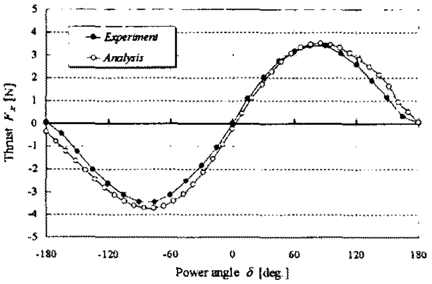


Fig. 5. Thrust versus power angle (slip=1.0).

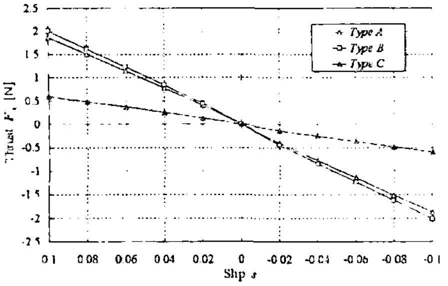


Fig. 6. Damping thrust versus slip.

4.2 Transient Characteristics

The self-starting and the reduction of hunting oscillations in synchronous drive of the proposed motor depend on the induction operation of field winding and solid-conductor in the secondary. Figure 7 shows the velocity versus distance in the synchronizing process by the ramp input of supply frequency (i.e., 2.5[Hz/s]) and the single frequency supply of f=10[Hz]. The process can be shortened by adopting higher supply frequency at starting and controlling the power angle in synchronism, as shown in Fig. 8.

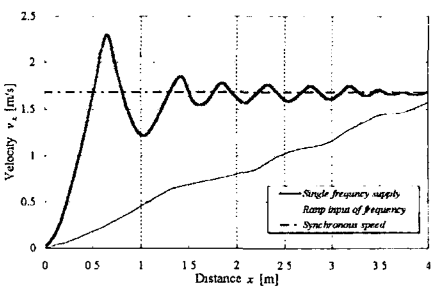


Fig. 7. Starting by normal methods (*Type B*).

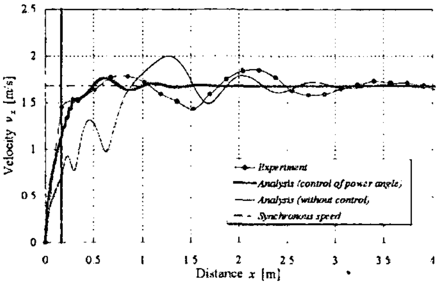


Fig. 8. Starting by two stages of supply frequencies (*Type B*).

5. CONCLUSIONS

The purpose of this paper is to derive both optimal secondary construction and driving method in the linear synchronous motor with induction operation. By arranging the additional secondary solid-conductor besides the field winding for electromagnet, we can improve the self-starting and damping effects. For investigating the dynamic and transient characteristics of the motor, we adopt finite element analysis coupled with electric circuit and motion equation.

By the analytical and experimental results, we confirm that that *Type B* in table 2 is most superior for the starting behavior. The secondary can be accelerated in an extremely short time by adopting two stages of supply frequencies. In addition, we can reduce the hunting oscillations in synchronism by controlling the power angle. From the above advantages, we conclude that the proposed motor is suitable for practical use and expected its application in the various fields of industrial circle [6], [7].

Acknowledgment

The authors would like to thank Mr. Kazuhito Hayashi of Nippon Telegraph and Telephone Corporation (NTT) in Japan for his assistance on the experiment.

REFERENCES

[1] T. Onuki, et al., "Secondary Construction Enhancing Damping Effects in the Permanent Magnet Type Synchronous Motor", Nonlinear Electromagnetic Systems, IOS Press, pp. 104-107, 1996.
[2] W.J. Jeon, et al., "Dynamic Characteristics of Synchronous Motors applying A Plural Magnets System to the Rotor", IEEE Trans. on Magnetics, Vol. 35, No. 5, pp. 3574-3576, 1999.
[3] K. Kurihara, et al., "Transient performance analysis of permanent magnet synchronous motors using the finite element analysis", Trans. of IEE Japan, Vol. 114-D, No. 5, pp. 551-560, 1994.
[4] T. Onuki, et al., "Improvement of Short Primary Member Linear Induction Motor Performance by Partial Adoption of the Wound Secondary", Conf. record of IEEE-IAS'98, Vol. 1, pp. 179-186, 1998.
[5] T. Nakada and N. Takahashi, "Direct Finite Element Analysis of Flux and Current Distributions under Specified Conditions", IEEE Trans. on Magnetics, Vol. 18, No. 2, pp. 325-330, 1982.
[6] D. Ebihara, et al., "Fundamental Construction of Linear Hybrid Motor by LSM and LPM", Paper of Technical Meeting on Linear Drives, LD-90-26, IEE of Japan, 1990.
[7] D. Ebihara, et al., "The Research Trends of Linear Drives in the Recent Two Years", Paper of Technical Meeting on Linear Drives, LD-97-101, IEE of Japan, 1997.
[8] Jacek F. Gieras and Zbigniew J. Piech, "LINEAR SYNCHRONOUS MOTOR", CRC Press, 1999.