An Approach Toward Improving Performance of Moving Coil Type Linear Oscillatory Actuator Considering Asymmetric Magnetic Circuit

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***Abstract*—This paper proposes an approach toward improving the performance of Moving Coil type Linear Oscillatory Actuator (MC-LOA) with a core design and a simple controller. The approach is formulated on the analysis of an asymmetric magnetic circuit of MC-LOA by Finite Element Method (FEM). Due to the asymmetric magnetic circuit, MC-LOA tends to have unbalanced thrust along current directions. In order to overcome this drawback, a saturation effect is applied to the core design, and the controller founded on thrust estimation with FEM is used for the input of MC-LOA. The propriety of this approach is verified by experimental results.**

Index Term—Asymmetric structure, FEM, MC-LOA and PWM

I. INTRODUCTION

Linear electric machines are founded to increase rapidly its variety of application such as short stroke linear vibrators recently. Among them, Moving Coil type Linear Oscillatory Actuator (MC-LOA) is suitable for such a short stroke reciprocating system. Furthermore, MC-LOA including Permanent Magnet (PM) with high specific energy is applicable for the large capacity industrial machine [1].

However, MC-LOA has an unbalanced magnetic circuit due to its asymmetric structure and there is a different flux distribution on the air-gap along the current direction. Interaction of two fluxes between the PM and the current causes the unbalanced thrust and interferes with the proper oscillation of MC-LOA [1-2].

The aim of this paper is to find a proper way to resolve the above-mentioned problems and to improve the driving performance of MC-LOA. For this, it is necessary to estimate the rate of the unbalanced thrust according to the current direction. This estimation enables to design the machine having the balanced magnetic circuit and to adopt a simple control method without an intricate structure.

Since MC-LOA has an asymmetric structure, it is very important to perform the core design [3]. Therefore, the characteristic analysis of MC-LOA is achieved by Finite Element Method (FEM) in order to predict its performance. From the analysis results, it is confirmed that the rate of saturation in core has a great influence on the thrust characteristic. In other words, the increase of the saturation rate causes the decrease of thrust difference along the current direction. For this reason, although a general electric machine design should avoid the saturation effect, this paper proposes the improved model for the balanced magnetic circuit that is designed to have the minimized unbalanced thrust by using a saturated core.

The improved model, however, introduces shortcomings of reduced thrust and efficiency. Even if these shortcomings can be eliminated with a certain specific controller that eventually improves the MC-LOA performance, it needs a lot of cost and technique to compose the complex whole system. However, the proper controller design can be found by applying the results of the characteristic analysis with FEM. In this study, an open loop control method is therefore selected as one of the effective and simple control system.

In order words, the core design considering the saturation effect is first performed with FEM and the design result is applied to the selected control system. This approach can achieve not only minimizing the disadvantage of the improved model but also simplifying the control system

II. INITIAL DESIGN

The initial design of MC-LOA having sinusoidal displacement along time variation is achieved by Equivalent Magnetizing Circuit (EMC) method. The combined equations of kinetic and electric equations for the designed MC-LOA are as follows [3].

$$F = Ma + Dv \quad (1)$$

$$F_m = N B_g I l = K_f I \quad (2)$$

where F is thrust (N), M is load mass (kg), D is friction coefficient, v is velocity (m/sec), F_m is Lorentz force (N), N is number of coil turns, B_g is air-gap flux density (T), I is current (A), l is actual length of coil (m), and K_f is thrust constant.

In this case, thrust (F) and Lorentz force (F_m) are coupled each other and they have same values. The required specification of MC-LOA such as the maximum stroke, operating frequency, input current and total load mass are ±3 (mm), 12 (Hz), 3 (A, peak to peak) and 3 (kg), respectively.

Fig. 1 shows the design process of MC-LOA. When designing the magnetic circuit, it is usually difficult to estimate accurately the leakage, saturation and Magneto Motive Force (MMF) loss coefficients with EMC. This paper,

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therefore, applies FEM to compensation of these coefficients in design stage.

MC-LOA has the symmetric structure along up y-axis. Therefore, the half model is selected for the analysis model and dirichlet boundary condition is applied to it. The governing equation of the analysis model is as follows [4].

$$\frac{1}{\mu}\frac{\partial^2 A}{\partial x^2} + \frac{1}{\mu}\frac{\partial^2 A}{\partial y^2} = -(J_0 + J_m) \tag{3}$$

where μ is magnetic permeability, A is magnetic vector potential, J_0 is supply current density and J_m is magnetizing current density.

Leakage coefficient in MC-LOA is lager than that of rotational machines because there is PM in mechanical air-gap. It must be compensated by the accurate estimation of factors, such as core thickness considering the saturation effect and side distance illustrated in Fig. 2. The specification of the designed model achieved by initial design process is shown in Fig. 2 and TABLE I. It satisfies the above-mentioned required specification.

III. Characteristic Analysis using FEM

Fig. 3 shows the air-gap flux density distribution when coil and PM are excited and the mover is in the center of its displacement. As the mover goes on to inner core direction ($+x$), forward direction, the air-gap flux density has a larger value than the other case that the mover goes to the opposite direction ($-x$), backward direction. This is due to the unbalanced magnetic circuit and the interaction caused by two fluxes between the PM and the current. This phenomenon causes the unbalanced thrust along the mover's direction and interferes with the proper oscillation of MC-LOA.

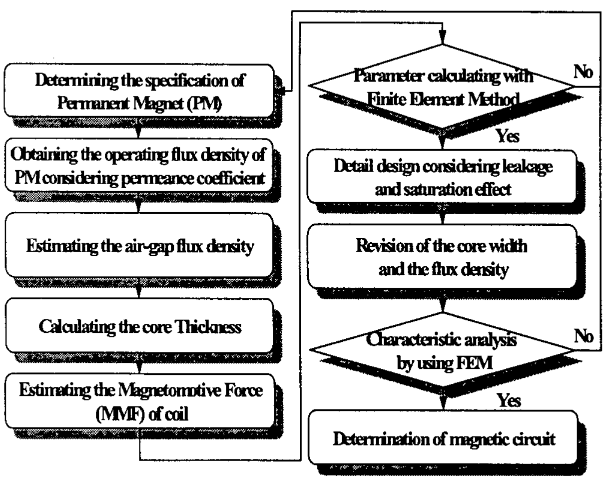


Fig. 1. Design process

The magnitude of unbalanced thrust along the mover direction is illustrated in Fig. 4. As the mover moves to forward direction, high thrust is maintained while low thrust is maintained for backward moving. The thrust difference for direction change is about 3.1 (N). The rate of thrust difference is caused by coil MMF. Therefore, decreasing the influence of coil MMF can reduce the rate of thrust difference.

TABLE I
Specifications of Initial Designed Model

Items		Value	Unit
Core	Thickness	25	mm
	Axial length	50	mm
PM	Residual magnetic flux density	1.15	T
	Width×length×height	65×50×15	mm^3
	Recoil permeability	1.05	
Coil	Number of turns	309	Turns
	Resistance	2.71	Ω
	Diameter	0.882	mm
	Conductor cross section	0.5	mm^2
Mechanical air-gap		3.43	mm
Friction coefficient		0.003	N·sec/m

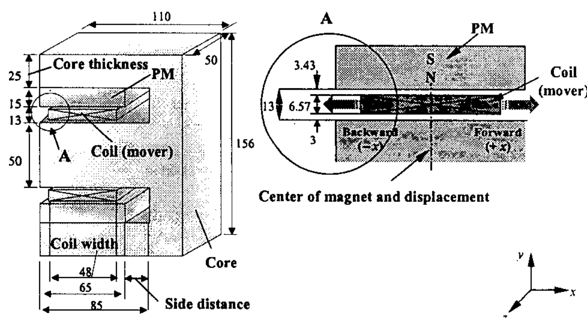


Fig. 2. Dimension of initial designed model(mm)

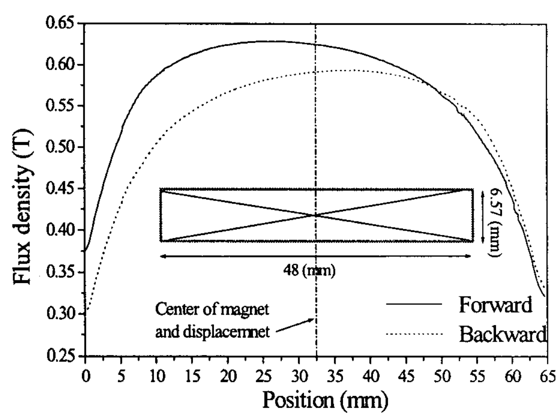


Fig. 3. Flux density distribution in air-gap

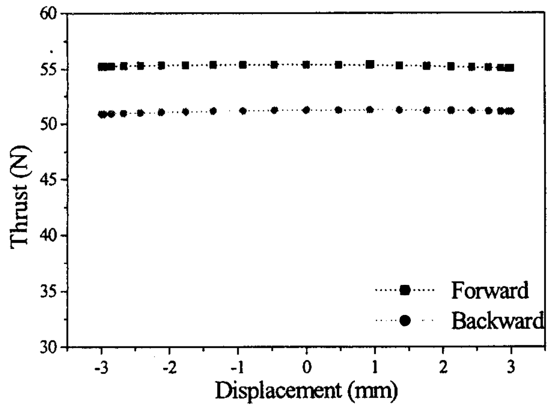


Fig. 4. Thrust according to mover displacement

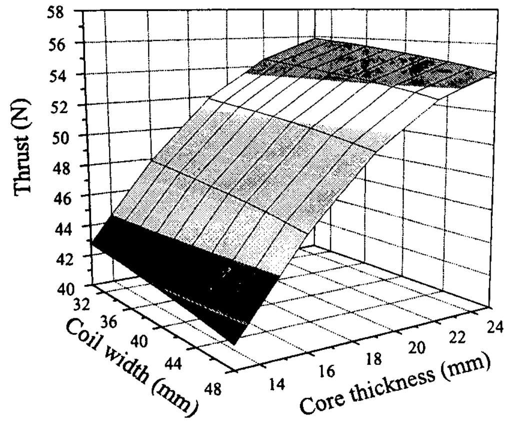


Fig. 5. Surface of thrust with coil width and core thickness

IV. Design Considering Unbalanced Thrust

The core design of MC-LOA having balanced magnetic circuit is performed for the minimized thrust difference along the mover directions. As long as the coil MMF is relatively smaller than PM MMF, the magnitude of thrust difference is decreased. Meanwhile, the rate of flux density saturation in core has a great influence on the above phenomenon [5-6]. This paper, hence, proposes the improved model that has the minimized thrust difference, and that could accurately estimate the rate of saturation by FEM for the variation of core thickness.

However, the saturation tends to cause the decrease of total thrust due to the increase of magnetic resistance in core. In order to compensate this shortcoming and change the thrust into the maximum value, the coil shape is treated with uniform coil cross section. Each thrust according to the design results is calculated by FEM [4]. The thrust characteristics for the variety of core thickness and coil width are presented in Fig. 5 and Fig. 6. As each core thickness and coil width decrease individually, the thrust difference and the total thrust are decreasing and increasing, respectively. In this case, the core thickness and the coil width are selected as 17(mm) and 31.54(mm) respectively for the improved model and it is illustrated in Fig. 7.

Fig. 8 shows the air-gap flux density distributions of the improved model. Comparing with the initial model, there are a few different distributions at each direction but their summations become similar values. In the initial designed model, the core flux densities along the forward and backward directions are about 1.71(T) and 1.58(T), respectively. The difference is about 8.2(%). In the case of the improved model, the each value is about 2.01(T) and 1.99(T) and its difference could be ignored. Consequently, the thrust difference is reduced less than 0.8(N) as shown in Fig.9.

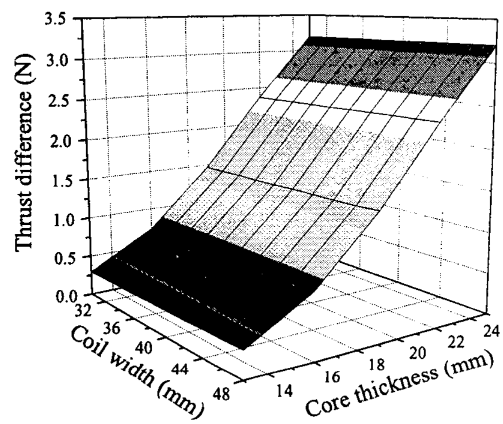


Fig. 6. Surface of thrust difference with coil width and core thickness

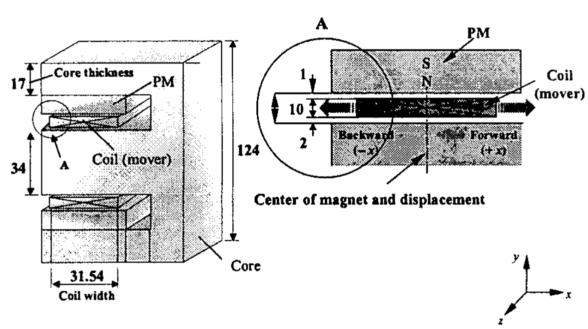


Fig. 7. Dimension of improved designed model (mm)

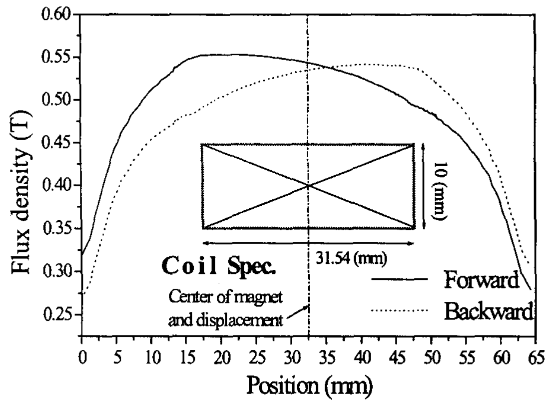


Fig. 8. Flux density distribution of improved model in air-gap

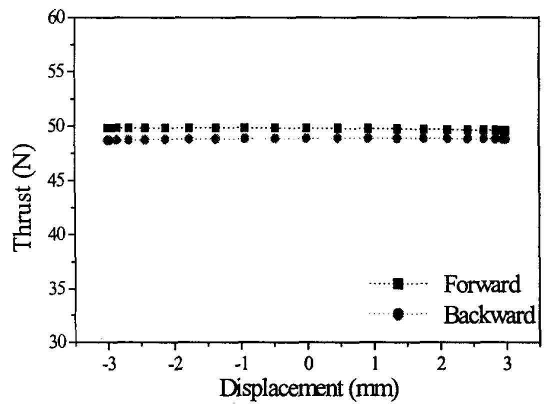


Fig. 9. Improved thrust according to mover displacement

V. Application of Control System

In order to minimize the thrust difference, the core thickness should be reduced to less than 13(mm) as shown in Fig. 6. However, this causes the decrease of thrust and efficiency. Although using a normal control system for MC-LOA can resolve these shortcomings, it requires a lot of cost and technique. Therefore, instead of using the complex control system, it is desirable to use a simple control method since the accurate analysis of MC-LOA's characteristic is allowed by using FEM. Fig. 10 shows the flowchart for the application of control system.

A. Calculation of Input Currents

The initial and improved model yield about 6.14(%) and 1.91(%) larger thrust for forward direction estimated by FEM have values than those for backward direction, respectively for the case with the input current is 3 (A, peak to peak) and required thrust is 52 (N). In addition, we can calculate the Lorentz force, F_m, and the thrust coefficient, K_f, in (2). With these calculated thrust coefficients, the input currents can be easily obtained along the moving directions in order to maintain the same thrusts. Each current value, Lorentz force and thrust coefficient are shown in TABLE II.

B. Control System

A simple control technique, in which subtracts the excess current values from the forward regions and adds the insufficient current values to backward region, can eliminate the unbalanced thrusts. Moreover, controlling the input current values can be easily performed by Pulse Width Modulation (PWM) method. TABLE III presents the specification of the control system.

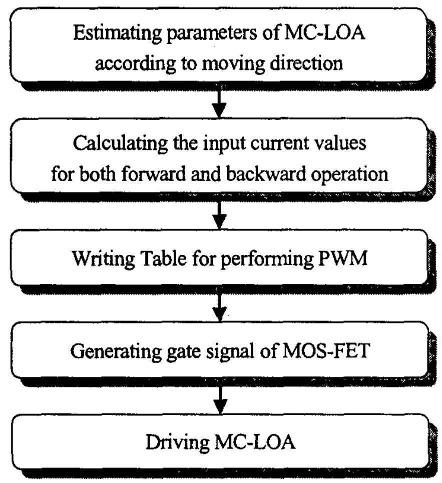


Fig. 10. Flowchart for control system

TABLE II
DETERMINING INPUT CURRENTS

Model	Moving direction	Lorentz force (N)	Thrust coefficient	Input current (A, peak to peak)
Initial model	Forward	54.26	18.09	2.87
	Backward	51.12	17.04	3.05
Improved model	Forward	49.62	16.54	3.14
	Backward	48.82	16.27	3.19

TABLE III
SPECIFICATION OF CONTROL UNITS

	Items		Specification
System	Main circuit mode		MOSFET type single phase inverter
	MOSFET rate		100 [V], 20 [A]
	Input voltage range		DC 0 ~ 15 [V]
	Output	Rated voltage	AC 12 ± 5% [V]
		Capacity	50 [VA]
		Rated frequency	12 ± 1% [Hz]
Control	CPU		8bit 8051 processor
	Control method		Open-loop control
	Control object		Current limit control

In this paper, MOS-FET is used to perform PWM for MC-LOA as a power device. 8051 processor and a table, in which contains the information of the gate on-off time ratio, T_G, are used to control the gate signal. In order to obtain the required currents, it is very important to determine T_G according to the moving directions. Fig. 11 shows the flowchart of PWM table. Half a period of operating frequency, 12 (Hz), is divided into equivalent N regions and the value is marked as T_1. T_2 is voltage value at each region. Depending on T_G, the input currents at each moving direction vary and they can fit in with the values in TABLE II.

Furthermore, in the case of the improved model, the difference between two T_Gs corresponding to each moving direction is less than the initial model. There is therefore a less burden in improved model than the initial one for the controller. Fig. 12 and 13 respectively show the block diagram for control system and the control diagram of PWM control system with 8051 processor.

VI. Comparison with Experimental Results

Dynamic characteristic analysis of MC-LOA depending on only FEM takes a lot of time, therefore, it is achieved by the combined equation of the voltage and kinetic equations. This equation is then coupled with time differential method and applied for the dynamic characteristic analysis according to time variation. In addition, the parameters, in which compose the voltage equation, are accurately estimated by FEM.

Fig. 14 (a) and (b) show each manufactured model and (c) illustrates the driving set for the experiment. Fig. 15 shows the measured thrust values of each model for the mover positions. They are in good agree with the analysis results illustrated in Fig. 4 and Fig. 9.Fig. 16 shows the experimental set to measure the displacement and current characteristics.

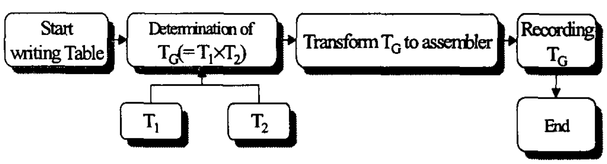


Fig. 11. Flowchart of PWM Table for half a period

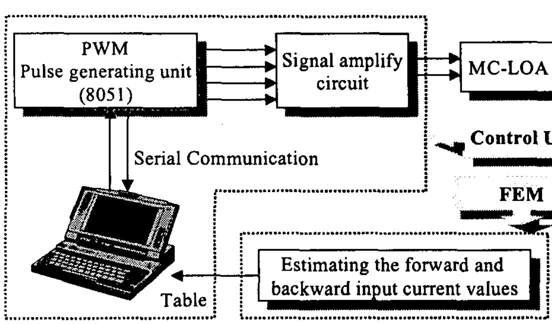


Fig. 12. Block diagram for control system

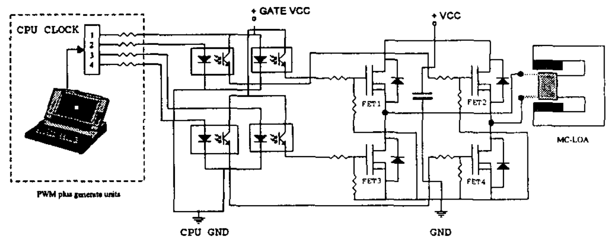
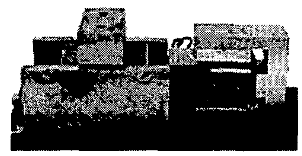


Fig. 13. Control diagram of PWM with 8051 processor

(a) Initial model



(b) Improved model

(c) Configuration of experimental model

Fig. 14. Test machine and driver

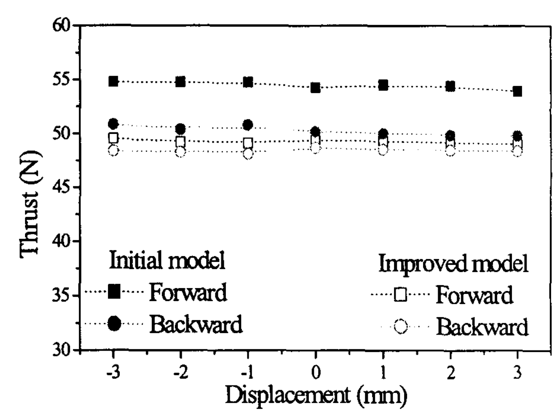


Fig. 15. Thrust according to mover direction (experimental value)

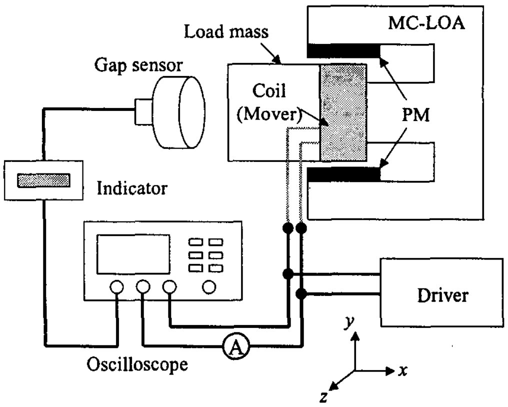


Fig. 16. Experimental set for the current and displacement characteristics

Fig. 17 (a) and (b) respectively present the driving experimental results of the initial designed model and the improved model without controlling the input current ratio along the mover direction. The former shows that the driving performance is getting worse even only within one second. The later shows the improved driving performance, however, it is still not proper enough for the required oscillation since the mover tends to move into forward direction. On the other hand, Fig. 18 (a) and (b) show the results of the driving experiments, in which control the input current ratio for each model. Both of them well satisfy the proper driving performance and the experimental results are in good agreement with the analysis results. Consequently, it is verified that controlling input current allows to obtain the required displacement characteristic as shown in Fig. 18 (a) and (b).

Fig. 19 (a) and (b) present measured currents when MC-LOA is driving with controlled current. It is noticeable that in the case of initial model in Fig. 19 (a), the current difference along moving directions is quite lager than that of the improved model and it can cause the stress of control system. Therefore, controlling the improve model would be more stable for the control system.

VII. Conclusion

This paper has proposed the approach toward improving the performance of MC-LOA. The unbalanced thrust along the current direction, which is caused by the asymmetric structure of MC-LOA, is accurately estimated by FEM. Both the initial and the improved model, which have respectively unsaturated and saturated core, are introduced. The characteristic analysis of both models is also performed by FEM and the analysis results are used for the control system in order to not only improve the driving performance of MC-LOA but also reduce the burden of the controller. The propriety of the proposed approaches is verified by the comparison with the experimental results.

Acknowledgment

This work was supported by the Korea Science and Engineering Foundation (KOSEF) through the Machine Tool Reach Center at Changwon National University

Reference

[1] Naila Mikhaei-Boules, "Design and analysis of linear actuator for active vibration cancellation", General Motors Corporation, 1995.

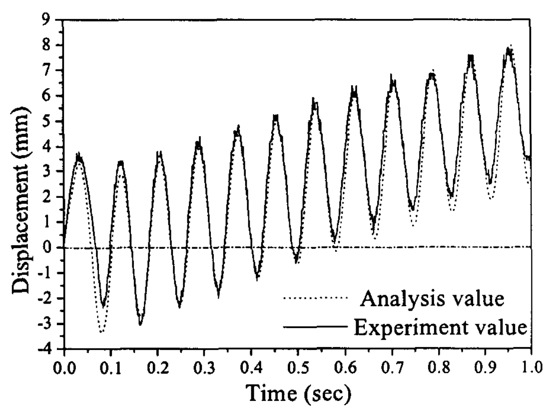
[2] H. Wakiwaka, H. Yajima, S. Senoh and H. Yamada, "Simplified Thrust Limit Equation of Linear DC Motor", *IEEE*, Vol. 32, pp. 5073-5075.

[3] R Akmese, J. F. Eastham, "Design of Permanent Magnet Flat Linear Motors for Standstill Application" *IEEE Trans.on Magn*, VOL. 28, NO. 5, pp. 3042-3044, 1992

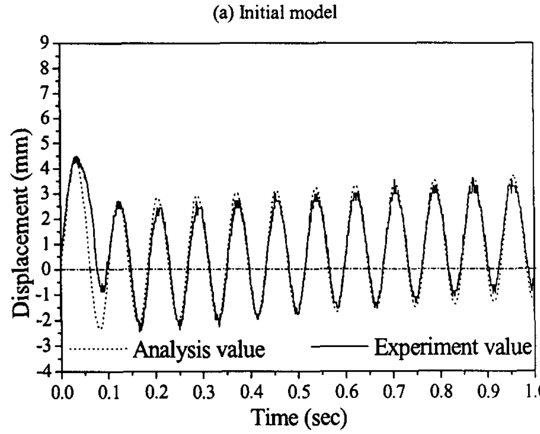
[4] Liuchen Chang, "In Improved FE Inductance Calculation for Electrical Machine", *IEEE Trans. J. Magn*, Vol. 32. No. 4, pp. 3237~3245, July. 1996

[5] P.J.Hor, Z.Q.Zhu, D.Howe, J.Rees-Jones "Minimization of Cogging Force in a Linear Permanent Magnet Motor", *IEEE Trans. J. Magn*, Vol. 34. No. 5, pp. 3544~3547,SEPT. 1998

[6] Dal-Ho Im, Jung-Pyo Hong, In-soung Jung, Sang-Baeck Yoon "The Optimum Design of Permanent Magnet Linear Synchronous Motor" *Proc. Of IEEE CEFC* '96.pp.166,1996



(a) Initial model



(b) Improved model

Fig. 17. Displacement characteristics without control system