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A STUDY ON PARAMETER IDENTIFICATION AND SENSORLESS CONTROL OF LINEAR COMPRESSORS

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ABSTRACT

A conventional reciprocating compressor uses a crank mechanism in order to change the rotational motion of a motor into linear motion. Accordingly, a reciprocating compressor can be operated safely by virtue of the crank mechanism, even though it makes the reciprocating compressor less efficient. However, the moving parts of a linear compressor are not constrained. Thus, the implementation of a closed-loop control system is necessary for the accurate control of piston position. In this paper, a closed-loop sensorless stroke control system for an oscillating linear motor has been designed. The motor parameters are identified as a function of the piston position and the motor current. They are stored in ROM table and used later for the accurate estimation of piston position. Some experimental results are given in order to show the feasibility of the proposed control schemes for linear compressors.

Keywords- *reciprocating compressor, closed-loop control, sensorless stroke control, oscillating linear motor, estimation of piston position, linear compressor.*

I. INTRODUCTION

In a house, a refrigerator consumes about 30% of the total electric energy and the compressor which circulates refrigerant through the refrigeration system consumes most of electric energy in a refrigerator. Hence, energy efficient compressors are essential for saving of household electric energy. Over the past several decades, a series of linear compressors have been developed for various applications in order to meet the need for efficient compressors.

Because all the driving forces in a linear compressor act along the line of motion, there is no sideways thrust on the piston. The compressor of this type substantially reduces sliding bearing loads. Thus, no need for the conversion mechanism and no sideways thrust make a linear compressor more efficient than a reciprocating compressor. In addition, the sudden peak noises which are generated as a reciprocating compressor is turned on and off can be eliminated in a linear compressor by virtue of the soft start-stop operation. These advantages of a linear compressor over a reciprocating one have encouraged refrigerator manufacturers to develop linear compressors for various applications, including domestic refrigeration.

It was shown that linear compressors had extremely low friction losses compared to other compressor types and high efficiency could be achieved for a variety of refrigerants and compressor sizes [1]. The problems associated with the linear motor configurations which are potentially applicable to linear compressors were discussed [2]. They described moving coil type and moving magnet type linear motors and two methods of the linear compressor control that had been successfully applied. Some non-refrigeration applications for linear compressors were also studied [3]. A small linear compressor which operates at 50Hz was designed for the european market which could serve a variety of small and portable coolers for specialty uses, including recreational or medical cooling [4]. The piston positioning accuracy and the efficiency of the sensorless linear compressor system with the linear pulse motor were examined using analytical and experimental approaches [5]. But, the motor parameters were not identified fully. A dual stroke and phase control system was proposed for linear compressors of a split-stirling cryocooler [6]. A linear compressor was developed for 680 liter household refrigerator [7]. It reduced the energy consumption of a refrigerator by 47% compared with a reciprocating compressor. In [8], they showed that LGE created the innovative linear compressor, which has much higher efficiency in the small cooling capacity. The refrigerator with this linear compressor shows that the power consumption reduction by 25% can be achieved, as compared with the reciprocating compressors.

The results of an investigation on the system dynamics and the controller design of a linear compressor for stroke and frequency adjustment were presented [9]. A system dynamics model was derived and identified experimentally. A control system was designed based on the system dynamics model. The control system used a PDF (Pseudo-

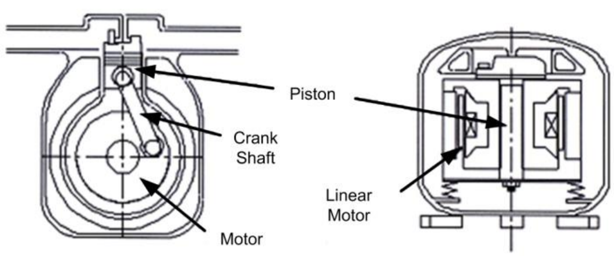
Derivative Feedback) algorithm. A linear compressor operated directly by commercial AC electricity was developed in order to reduce the cost by eliminating the expensive controller and to enhance the compatibility with various types of refrigerators [10]. Parameters of the linear compressor were adjusted to get robust performances against the fluctuations of load and outlet voltage. Results of experiments showed the start linear compressor maintained high efficiency and low noise as well as excellent reliabilities even in severe conditions of household refrigerators. The simulation and experimental investigations on the static and dynamic characteristics of a moving magnet linear motor and a moving magnet linear compressor were presented [11]. Also, the force and equilibrium characteristics of the linear motor have been predicted and verified by detailed static experimental analyses.

The performance of linear compressors using a pulse width modulation inverter is investigated, with emphasis on the efficiency and power factor along with variations of both mechanical and electrical resonant frequencies [12]. In [12], the strategy for improving the efficiency of the linear compressor was suggested by controlling the average value of the product of the piston stroke and motor current to 0. The mathematic model of the self-sensor was established by analyzing the moving magnet linear motor of linear compressor, and the measurement method of piston stroke was achieved [13]. In [13], the piston stroke can be calculated by measuring the voltage and current of the linear motor coil.

In this study, a closed-loop sensorless stroke control system for a linear compressor has been designed. The motor parameters are identified as functions of piston position and motor current. Then, they are stored in a read-only memory (ROM) table and used later for accurate estimation of piston position. The performances of the various motor parameter identification algorithms are evaluated by experimental studies.

II. SENSORLESS CONTROL OF LINEAR COMPRESSOR

Fig. 1(a) shows a conventional reciprocating compressor driven by a rotary motor coupled to a conversion mechanism. On the other hand, a linear compressor is a piston-type compressor in which the piston is driven directly by a linear motor as shown in Fig. 1(b). Because all the driving forces in a linear compressor act along the line of motion, there is no sideways thrust on the piston. A compressor of this type substantially reduces sliding bearing loads. Thus, there is no need for a conversion mechanism and the absence of sideways thrust makes linear compressors more efficient than reciprocating compressors. In addition, the sudden peak noises which are generated as a reciprocating compressor is turned on and off can be eliminated in a linear compressor by virtue of their soft start-stop operation. As can be seen from Fig. 1(a), a conventional reciprocating compressor uses a crank mechanism in order to change the rotational motion of the motors into linear motion. Accordingly, a reciprocating compressor can be operated safely by virtue of the crank mechanism, even though it makes the reciprocating compressor less efficient.



(a) reciprocating compressor (b) linear compressor

Fig. 1. Conventional reciprocating compressor and linear

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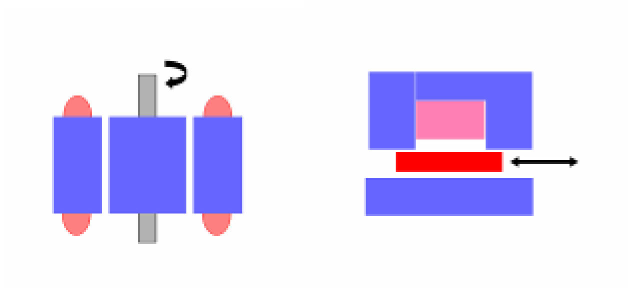


(a) reciprocating motor (b) linear motor

Fig. 2.Motion comparison of reciprocating motor and linear motor

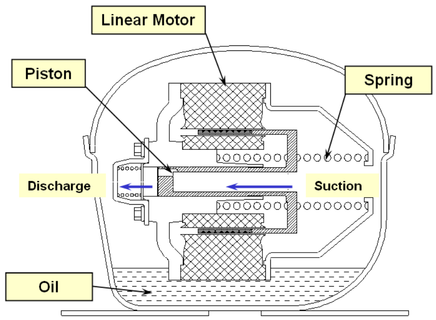
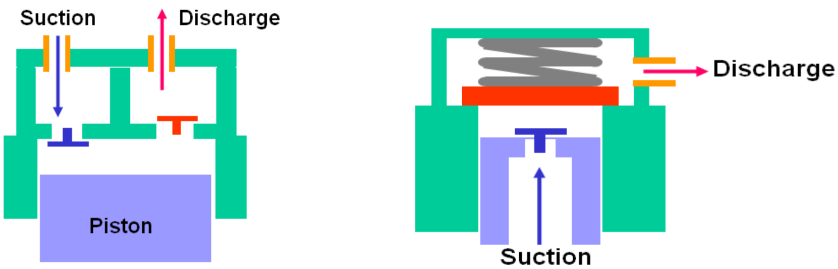


Fig. 3. A cross-section view of a linear compressor for refrigerators



(a) reciprocating compressor (b) linear compressor

Fig. 4.Valve comparison of reciprocating compressor and linear compressor

Fig. 2 (a) shows that the motor which is chosen for a conventional reciprocating compressor rotates. On the other hand, the linear motor of Fig. 2 (b) chosen for a linear compressor moves linearly. Fig. 3 shows the cross-section view of a linear compressor developed for refrigerators. Fig. 4 shows the valves of a reciprocating compressor and a linear compressor. This linear type of valve structure shown in Fig. 4 (b) has less flow resistance and less suction gas heating comparing with the reciprocating one shown in Fig. 4 (a).

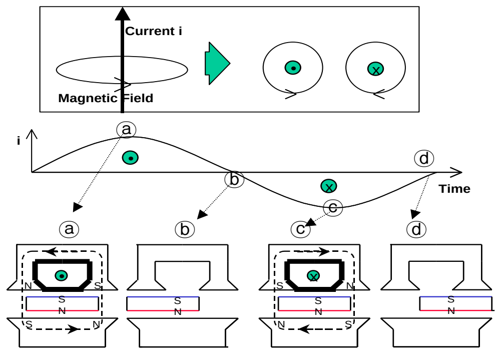


Fig. 5. Operating principle of an oscillating linear motor.

The operating principles of an oscillating linear motor are shown in Fig. 5. The magnetic field grows to itsmaximum in a counterclockwise direction as the AC current increases to a positive peak value (see ⓐof Fig. 5). This magnetic field forces the magnet to move to the left, reaching the leftmost position finally as the AC current decreases to zero (see ⓑof Fig. 5). Immediately, the AC current flows in the opposite direction, resulting in a clockwise magnetic field which forces the magnet to move to the right (see ⓒof Fig. 5). Finally, the magnet reaches the rightmost position as the AC current becomes zero again (see ⓓofFig. 5).

If the current is 60Hz AC, then the magnet will oscillate sixty times a second. The larger the amplitude of the AC current is controlled to be, the larger the amplitude of the vibration of the magnet becomes. This results in a higher linear speed for the piston attached to the magnet and a higher flow rate for the refrigerant in a linear compressor.

On the other hand, the moving parts of a linear compressor are not constrained. As a result, the implementation of a closed-loop control system is necessary for accurate control of the piston position. This control system needs information on the piston position. In order to measure the piston position, an inductive position sensor in which the inductor is a small stationary coil wound on a ferrite coil can be used. However, this type of position sensor is more expensive than a current sensor or a voltage sensor. It is also difficult to install a position sensor in a linear compressor. Hence, it is more desirable to estimate the piston position indirectly.

An estimate of the piston position can be calculated indirectly. The equivalent electrical circuit of a linear motor in a linear compressor can be modeled and expressed as the linear differential Eq. (1). The thrust force $F_e(t)$ is expressed in Eq. (2).

$$\alpha \frac{dx(t)}{dt} + L_e \frac{di(t)}{dt} + R_e i(t) = V(t) \qquad (1)$$

$$F_e(t) = \alpha i(t) \qquad (2)$$

Since the magnetic flux density varies depending on the piston position, the force constant$\alpha$and the effective inductance$L_e$are functions of the piston position. The effective resistance$R_e$is assumed to be constant because its variance, being negligible, is ignored. $V(t)$is the applied voltage to the linear motor, $i(t)$is the current flowing through the winding coil, and $x(t)$is the piston position. However, the mechanical equation of motion can be described as:

$$M \frac{d^2x(t)}{dt^2} + C \frac{dx(t)}{dt} + Kx(t) = \alpha i(t) - A_p \Delta P(t) \qquad (3)$$

where M, C, and K denote the equivalent mass, viscous damping coefficient, and spring constant, respectively. A_p is the cross-sectional area of the piston, $\Delta P(t)$ is the pressure difference between the compressor chamber and the back surface of the piston. Taking the Laplace transform of the above Eqs. (1–3) yields:

$$X(s) = G(s)V(s) + W(s)\Delta P(s) \quad (4)$$

$$G(s) = \frac{\alpha}{ML_e S^3 + (MR_e + CL_e)S^2 + (CR_e + \alpha^2 + L_e K)S + R_e K} \quad (5)$$

$$W(s) = \frac{(L_e S + R_e)A_p}{ML_e S^3 + (MR_e + CL_e)S^2 + (CR_e + \alpha^2 + L_e K)S + R_e K} \quad (6)$$

A closed-loop linear compressor control system needs piston position information. In order to measure the piston position, an inductive position sensor, in which the inductor is a small stationary coil wound on a ferrite coil, can be used. However, this position sensor is more expensive than a current or voltage sensor. It is also hard to install a position sensor in a linear compressor. Hence, it is more desirable to estimate the piston position indirectly. Rearranging Eq. (1), one obtains:

$$\frac{dx(t)}{dt} = \frac{1}{\alpha}\left(V(t) - L_e\frac{di(t)}{dt} - R_e i(t)\right) \quad (7)$$

The estimated value of the piston position can be obtained by integrating Eq. (7):

$$\hat{x}(t) = \int_0^t \left(\frac{dx}{d\tau}\right) d\tau = \frac{1}{\alpha}\int_0^t [V(\tau) - R_e i(\tau)]d\tau - \frac{L_e}{\alpha} i(t) \quad (8)$$

For a digital control system, $\hat{x}(t)$ can be modified to digital form as

$$\hat{x}(n) = \frac{T}{\alpha}\sum_{k=1}^{n}\left(\frac{V(k-1)+V(k)}{2}\right) - \frac{TR_e}{\alpha}\sum_{k=1}^{n}\left(\frac{i(k-1)+i(k)}{2}\right) - \frac{L_e}{\alpha}i(n),\ n = 1, 2, 3, \cdots (9)$$

where T is the sampling period.In general, the stroke is defined as the distance between the top and bottom piston positions during one cycle of operation (i.e., the peak-to-peak value of piston position). Therefore, the estimated stroke can be easily calculated using the estimated piston position. Let a 90^o phase delay filter $H_d(s)$ be defined as:

$$H_d(s) = \frac{2\pi f - s}{2\pi f + s} \quad (10)$$

where f is the running frequency of the piston. If $\hat{x}_d(t)$ is assumed to be the 90^o phase delayed output of $\hat{x}(t)$, then the estimated stroke $\hat{z}(t)$ can be calculated as

$$\hat{z}(t) = 2\sqrt{\hat{x}^2(t) + \hat{x}_d^2(t)} \quad (11)$$

Fig. 6 shows the block diagram of the closed-loop sensorless stroke control system for a linear compressor. The applied voltage $V(t)$ and the motor current $i(t)$ are measured and input to the digital signal processor (DSP) central processing unit (CPU) chips after analog-to-digital (A/D) conversion. These measured variables, together with motor parameters, are used to estimate the piston position as shown in Eq. (9). The estimated stroke $\hat{Z}(s)$ is compared with the set-point value of the stroke $Z^*(s)$ which is determined depending on load conditions.The output of the proportional–derivative (PD) stroke controller is the set-point value of the amplitude of the motor current. The inner proportional–integral (PI) current controller is intended to minimize the effects of back EMF and current transients on the outer stroke control loop.

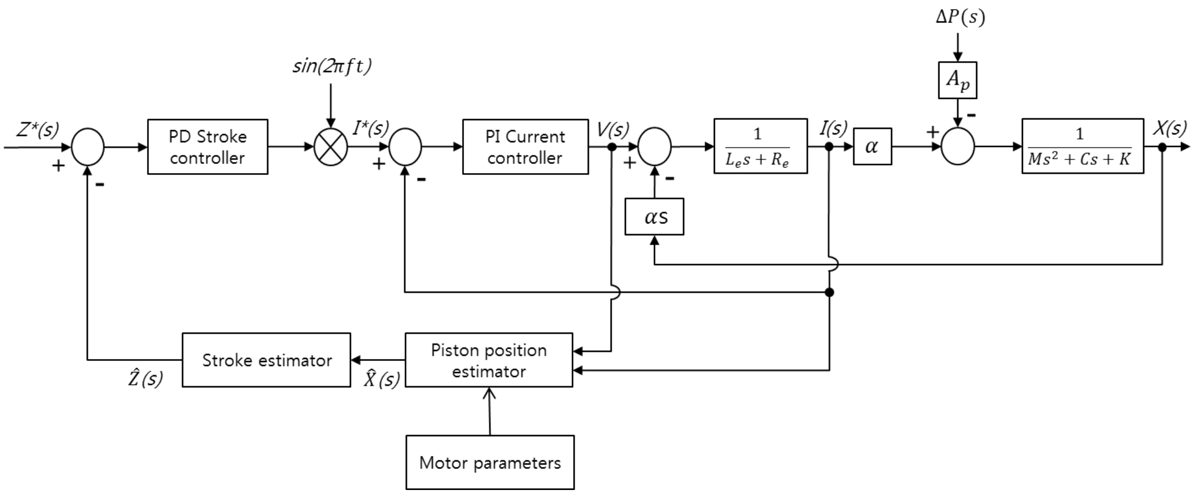


Fig. 6.Block diagram of the closed-loop sensorless stroke control system.

III. IDENTIFICATION OF MOTOR PARAMETERS

As mentioned earlier, the motor parameters α and L_e vary depending on the piston position. Therefore, if one assumes that the motor parameters are constant, then the estimated piston position expressed in Eq. (9) (or Eq. (8)) will have some errors, resulting in deterioration of the dynamic performance of the closed-loop sensorless stroke control system shown in Fig. 6.

The motor parameters α and L_e, which have substantial influence on the dynamic performance of the closed-loop stroke control system, should be identified as functions of piston position and motor current, stored in a ROM table, and used for the accurate estimation of piston position. In general, for any operating condition of refrigerators or air conditioners, there exists an optimal stroke value for maximum efficiency. Therefore, if there are some errors in the strokeestimate, it would be difficult to achieve maximum efficiency.

From Eq. (1), one obtains:

$$\hat{\alpha}x(t) + \hat{L}_e i(t) = \int_0^t [V(\tau) - R_e i(\tau)]d\tau \quad (12)$$

Note that $x(t)$, $i(t)$,and $V(t)$ in Eq. (12) are the measured values using a piston position sensor, a current sensor, and a voltage sensor, respectively. Note also that $\hat{\alpha}$ and $\ddot{L}_e$ are the identified values of α and L_e,respectively.

Let t_n be a period of the piston moving linearly in the steady state. By dividing t_n into n equal time intervals such as 0,t_1,t_2,...,t_{n-1},t_n, Eq. (13) is obtained using Eq. (12).

$$\hat{\alpha}x(t_1) + \hat{L}_e i(t_1) = \int_0^{t_1} [V(\tau) - R_e i(\tau)]d\tau$$

$$\hat{\alpha}x(t_2)+\hat{L}_e i(t_2)=\int_0^{t_2}[V(\tau)-R_e i(\tau)]d\tau \quad (13)$$
$$\vdots$$
$$\hat{\alpha}x(t_n)+\hat{L}_e i(t_n)=\int_0^{t_n}[V(\tau)-R_e i(\tau)]d\tau$$

Rearranging Eq. (13) into matrix form, one can obtain:

$$\mathrm{A}\begin{bmatrix}\hat{\alpha}\\ \hat{L}_e\end{bmatrix}=b \quad (14)$$

where $n\times 2$ matrix A and $n\times 1$ vector b are given as:

$$\mathrm{A}=\begin{bmatrix}x(t_1) & i(t_1)\\ x(t_2) & i(t_2)\\ \vdots & \vdots\\ x(t_n) & i(t_n)\end{bmatrix}, b=\begin{bmatrix}\int_0^{t_1}[V(\tau)-R_e i(\tau)]d\tau\\ \int_0^{t_2}[V(\tau)-R_e i(\tau)]d\tau\\ \vdots\\ \int_0^{t_n}[V(\tau)-R_e i(\tau)]d\tau\end{bmatrix} \quad (15)$$

Using pseudo inverse manipulation, one can obtain Eq. (16) from Eq. (14).

$$\begin{bmatrix}\hat{\alpha}\\ \hat{L}_e\end{bmatrix}=(A^TA)^{-1}A^Tb \quad (16)$$

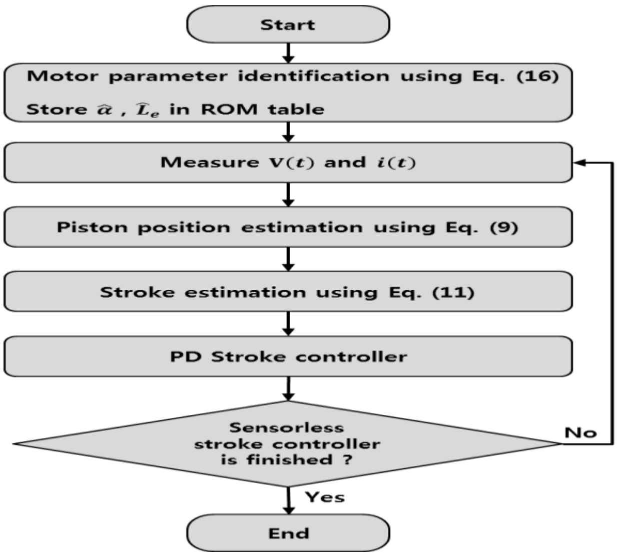


Fig. 7. Flow chart for the stroke control using PIM

Fig. 7 shows a flow chart for the closed-loop sensorless stroke control using the motor Parameters Identification Method (PIM) shown in eq (16). First, a linear variable differential transformer (LVDT) is installed on the liner motor to measure the piston position. Then, a closed-loop stroke control system is implemented,and $x(t_i)$, $i(t_i)$,and

$V(t_i)$ i= 1, 2, … n are measured in the steady state. Using these n measured state variables, the identified motor parameters $\hat{\alpha}$ and $\hat{L}_e$ are obtained using Eq. (16) and stored in the ROM table. Next, the sensorless stroke control loop is executed repeatedly.

IV. EXPERIMENTAL RESULTS

Asensorlessstroke controller for linear compressors has been implemented as shown in Fig. 8. The CPU chip is a TMS320C2000 (Texas Instruments, USA).For experimental study, a 2.2 kW linear compressor is chosen as shown in Table 1. The set-point value of the stroke is 0.02 m. The running frequency is set to 60 Hz.

The identified motor parameters $\hat{\alpha}$ and $\hat{L}_e$obtained using Eq. (16) are shown in Figs. 9and10, respectively. As can be seen from Fig. 9, $\hat{\alpha}$ is approximately 30–55 N/A for the piston position in the range of−0.012m< $x(t)$ <0.012m, and the current is in the range of −15A < $i(t)$ <15A. However, one can observe from Fig. 10 that $\hat{L}_e$ is approximately 0.03–0.12 H for the same range of the piston position and the current.

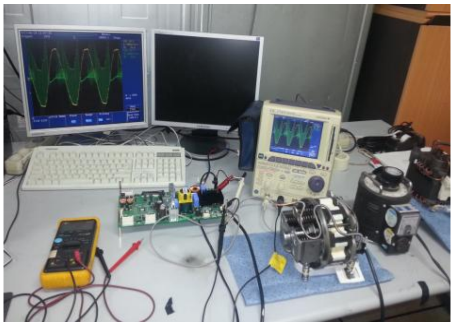


Fig. 8. Implemented experimental apparatus.

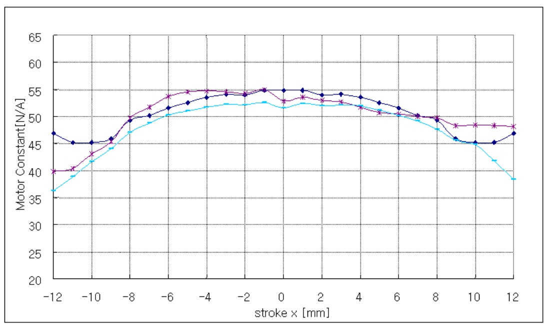
Table 1. Linear motor specifications

Rated output power	2.2 kW
Rated voltage	220 V_{rms}
Rated current	7 A_{rms}
Rated stroke	0.02 m
Resonant frequency	60 Hz
	2.5 Ω
	55 N/A
	0.12 H

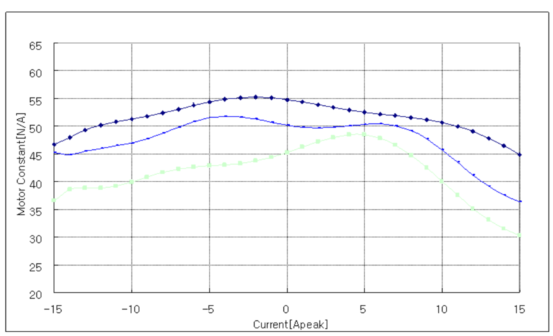
Up to now, it has been found to be costly and difficult to install a piston position sensor for measuring the stroke. It hasalso been found that piston position estimation requires information of the motor parameters which are not constant and vary as functions of the piston position and the motor current. Therefore, the motor parameters α and L_e, which have substantial influence on the dynamic performance of the closed-loop stroke control system, should be identified as functions of piston position and motor current, stored in ROM table, and used for accurate estimation of piston position. However, PIM has the demerit of demanding a large memory space for storing the identified motor parameters.

Finally, the stroke control error is compared. In the closed-loop sensorless stroke control system shown in Fig. 6, the stroke command is set to be 0.011 m. In the steady state, the stroke errors of 5.2%, 1.7%are obtained, for Constant, PIM, respectively. A similar experimental study was donewhile the stroke command was increasedfrom 0.011 to 0.019 m. Fig. 11 shows the experimental results of the stroke control error versus stroke command. In this experiment, it is shown that the average values of stroke error were 6.36% ,1.74%, for Constant, PIM, respectively.

Up to now, it has been found to be costly and not easy to install a position sensor for measuring the stroke. It was also found that the estimated stroke calculated with constant motor parameters generated substantial errors. On the other hand, the estimated stroke calculated with identified motor parameters generated comparatively small errors.

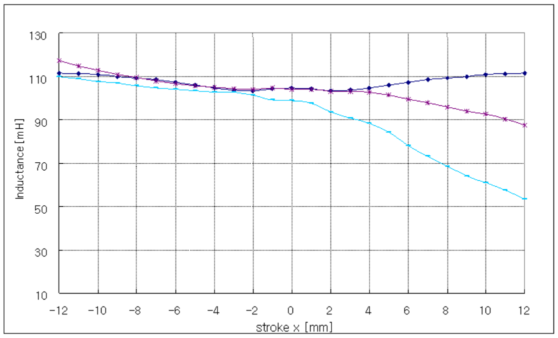


(a) Plot of $\hat{\alpha}$ as a function of stroke x

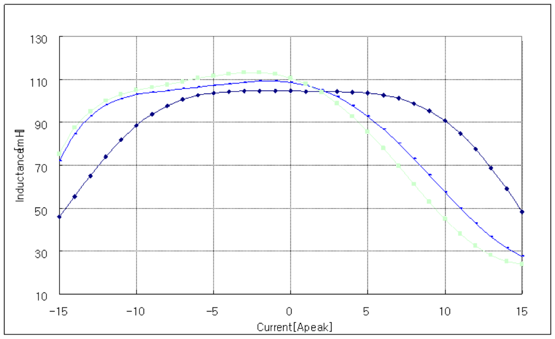


(b) Plot of $\hat{\alpha}$ as a function of current i

Fig. 9 Experimental results for $\hat{\alpha}$



(a) **Plot of $\hat{L}_e$ as a function of stroke x**



(b) Plot of $\hat{L}_e$ as a function of current i

Fig. 10 Experimental results for $\hat{L}_e$

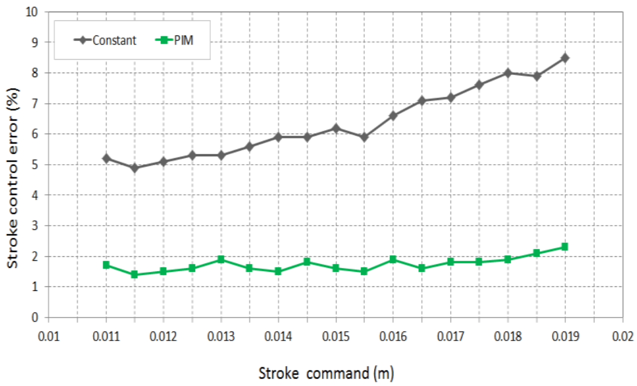


Fig. 11.Stroke control error versus stroke command.

V. CONCLUSIONS

In this paper, a closed-loop sensorless stroke control system for a linear compressor has been designed. The motor parameters are identified as functions of the piston position and motor current. Then, they are stored in a ROM table and used later for accurate estimation of piston position. The performances of the various motor parameter identification algorithms are evaluated by experimental studies.Compared with the stroke data obtained using the measured stroke, the stroke of the control system using PIM was controlled within a 2% error. However, PIM has the demerit of demanding a large memory space for storing the identified motor parameters. But, the method Constant which does not need any spare memory made the stroke control error of 6 to 7%.

VI. ACKNOWLEDGEMENT

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