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APPLICATION OF ABRUPT SHUT-DOWN ALGORITHM FOR PISTON AMPLITUDE ESTIMATORS 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. But, no need for the conversion mechanism and no sideways thrust make a linear compressor more efficient than a reciprocating compressor. These advantages of a linear compressor over a reciprocating one have encouraged refrigerator manufacturers to develop linear compressors for various applications, including domestic refrigeration. Because the moving parts of a linear compressor are not constrained, the implementation of a closed-loop control system is necessary for accurate control of the piston position. In this paper, an abrupt shut-down algorithm of linear motor piston amplitude estimators has been implemented. The dynamic performance of linear compressors depends on how accurately the stroke or the piston amplitude is estimated. A linear motor piston amplitude estimator using abrupt shut-down algorithm is proposed and the superior performance of our estimator is verified via some simulation studies.

Keywords- *reciprocating compressor, linear compressor, closed-loop control, piston amplitude estimator, abrupt shut-down algorithm.*

I. INTRODUCTION

Many countries such as U.S., EU, and Japan have some kind of energy regulation programs to decrease energy cons umption of the electric home appliance. In a house, a refrigerator consumes about 30% of the total electric energy an d the compressor which circulates refrigerant through the refrigeration system consumes most of electric energy in a refrigerator. So, energy efficient compressors are essential for saving of household electric energy. Over the past sev eral decades, a series of linear compressors have been developed for various applications in order to meet the need f or efficient compressors [1-7].

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.[7] 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 studied.[3] A small linear compressor which operates at 50Hz was designed for the European market.[4] It could serve a variety of small and portable coolers for specialty uses, including recreational or medical cooling. 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, they didn't identify the motor parameters fully. The 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.

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In this paper, an abrupt shut-down algorithm of linear motor piston amplitude estimators has been implemented. The dynamic performance of linear compressors depends on how accurately the stroke or the piston amplitude is estimated. A linear motor piston amplitude estimator using abrupt shut-down algorithm is proposed and the superior performance of our estimator is verified via some simulation studies.

II. ABRUPT SHUT-DOWN ALGORITHM OF LINEAR COMPRESSOR

Fig. 1 shows the cross section of a linear compressor developed for refrigerators. The conventional reciprocating compressor uses a crank mechanism in order to change rotational motion of motors into linear motion. Accordingly, the reciprocating compressor can be operated safe by the crank mechanism, even though it makes the reciprocating compressor less efficient. On the other hand, the moving parts of a linear compressor are not constrained by a crank mechanism. So, the closed loop control system for the accurate control of piston position is necessary. It needs the information of 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 position sensor is costly. It is also hard to install the position sensor in a linear compressor. So, it is more cost-effective to estimate the position indirectly.

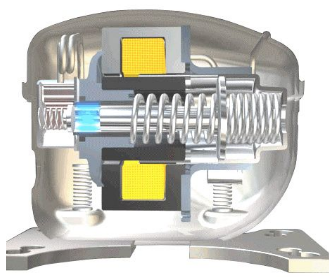

Fig. 1. Cross section of a linear compressor for refrigerators

We will now estimate the piston position indirectly. The equivalent electrical circuit of linear motors can be modeled like Fig. 2. From the circuit model of Fig. 2, we can get the linear differential eq. (1). The thrust force can be expressed in eq. (2).

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

$$F_e(t) = \alpha i(t) \tag{2}$$

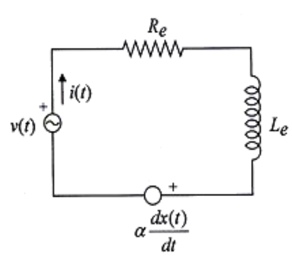

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Fig. 2. Equivalent electrical circuit model linear motors

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

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

where , , and denote the equivalent mass, viscous damping coefficient, and spring constant, respectively. is the cros s-sectional area of the piston, is the pressure difference between the compressor chamber and the back surface of th e piston. Taking the Laplace transform of the above Eqs. (1–3) yields:

$$X(s) = G(s)V(s) + W(s)\Delta P(s) \tag{4}$$

$$G(s) = \frac{\alpha}{ML_eS^3+(MR_e+CL_e)S^2+(CR_e+\alpha^2+L_eK)S+R_eK} \tag{5}$$

$$W(s) = \frac{(L_eS+R_e)A_p}{ML_eS^3+(MR_e+CL_e)S^2+(CR_e+\alpha^2+L_eK)S+R_eK} \tag{6}$$

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:

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

The estimated value of the piston position in the case of abrupt shut-down can be obtained by integrating Eq. (7) with :

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

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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° phase delay filter be defined as:

$$H_d(s) = \frac{2\pi f - s}{2\pi f + s} \tag{9}$$

where is the running frequency of the piston. If is assumed to be the 90° phase delayed output of , then the estimate d stroke can be calculated as

$$\hat{z}(t) = 2\sqrt{\hat{x}^2(t) + \hat{x}_d^2(t)} \tag{10}$$

Fig. 3 shows the block diagram of the closed-loop sensorless stroke control system for a linear compressor. The applied voltage and the motor current 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. (8). The estimated stroke is compared with the set-point value of the stroke 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.

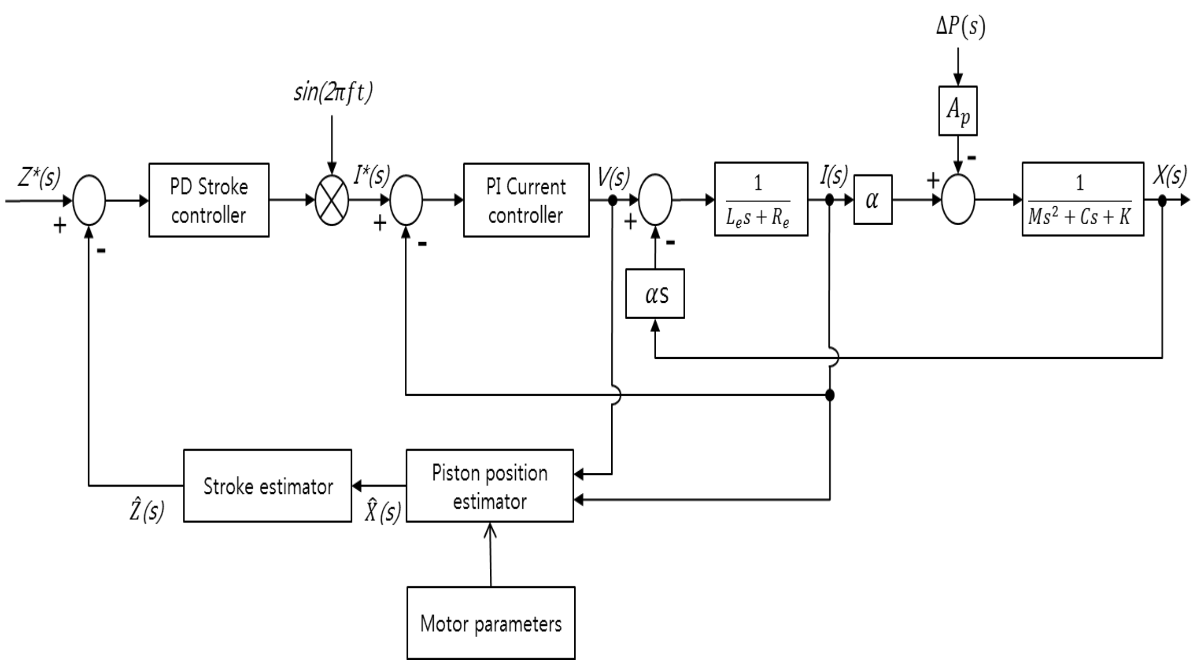

Fig. 3. Block diagram of the closed-loop sensorless stroke control system.

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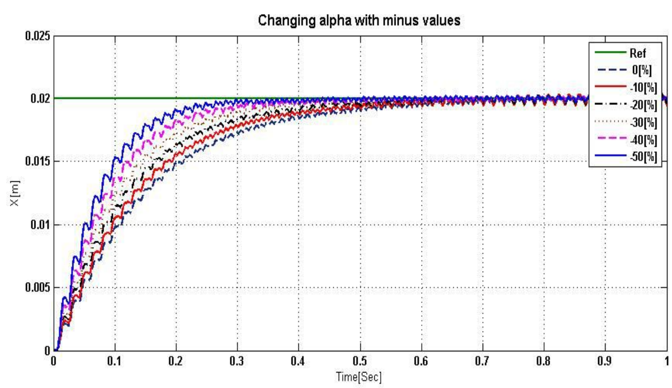
III. SIMULATIONAL STUDIES

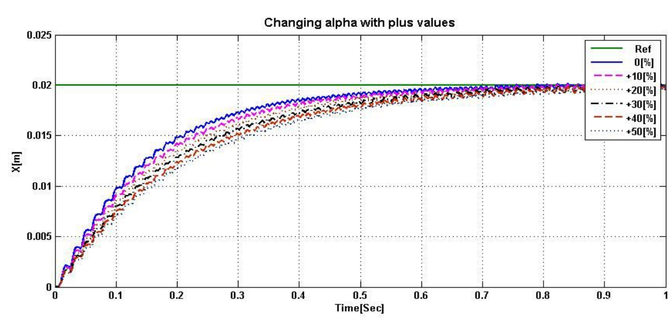
For simuational study, a 2.2 kW linear compressor is chosen as shown in Table 1. The set-point value of the stroke is 0.02 m. The running frequency is set to 60 Hz.

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



(a) **Under- estimated error of**



(b) **over- estimated error of**

Fig. 4 piston position response with estimation error of α

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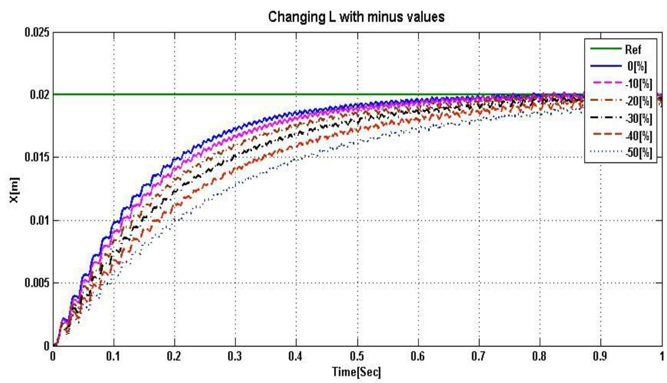
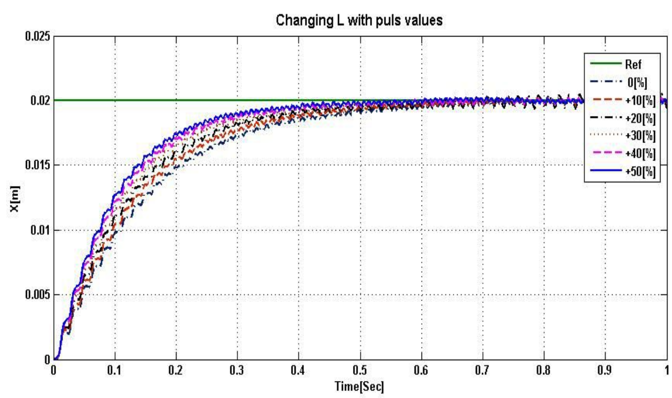
Fig. 4 shows the transient responses of the piston position in the case of estimation error of α. On the other hand, Fig. 5 shows the transient responses of the piston position in the case of estimation error of. Fig. 6 shows the transient responses of the piston position when the abrupt shut-down algorithm is applied at t = 1 sec. As can be seen in Eq. (8), the estimated value of the piston position is robust against the variation of or . But, this algorithm has the demerit of short shut-downing of current.



(a) **under- estimated error of**



(b) **over- estimated error of**

Fig. 5 piston position response with estimation error of

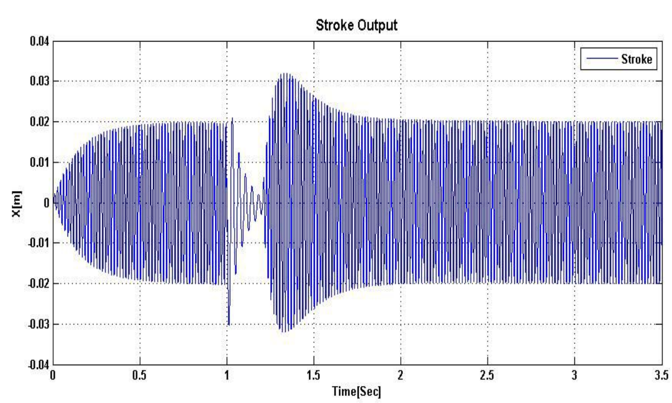


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Fig. 6 abrupt shut-down response of piston position estimation

IV. CONCLUSIONS

In this paper, a closed-loop sensorless stroke control system for a linear compressor has been designed. An abrupt shut-down algorithm of linear motor piston amplitude estimators has been implemented. The dynamic performance of linear compressors depends on how accurately the stroke or the piston amplitude is estimated. A linear motor piston amplitude estimator using abrupt shut-down algorithm is proposed and the superior performance of our estimator is verified via some simulation studies. We showed that the estimated value of the piston position was robust against the variation of or . But, this algorithm has the demerit of short shut-downing of current.

V. ACKNOWLEDGEMENT

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