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Sensorless Control for Linear Compressors

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Abstract: A closed-loop sensorless stroke control system for a linear compressor 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. Also it was attempted to approximate the identified motor parameters to the 2nd-order surface functions. Some experimental results are given in order to show the feasibility of the proposed control schemes for linear compressors.

Keywords: sensorless stroke control, linear compressor, identified motor parameters

1. INTRODUCTION

Many countries such as U.S., EU, and Japan have some kind of energy regulation programs to decrease energy consumption of the electric home appliance. 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 [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.

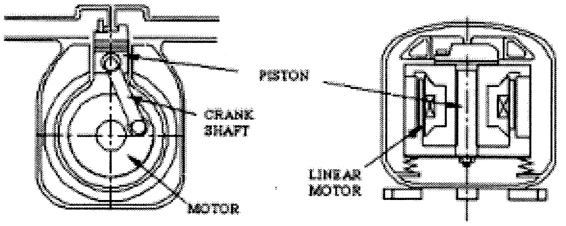
It was shown that linear compressors had extremely low friction losses compared to other compressor types and high efficiency can be achieved for a variety of refrigerants and compressor sizes.[1] The problems associated with the linear motor configurations which are potentially applicable to linear 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 this paper, a closed-loop sensorless stroke control system for a linear compressor has been designed. In order to estimate the piston position accurately, motor parameters were identified as a function of the piston position and the motor current. These parameters are stored in ROM table and used later for the accurate estimation of piston position. It was also attempted to approximate the identified motor parameters to the 2nd-order surface functions. Several experimental results have been obtained in order to show the feasibility of the proposed control schemes for linear compressors.

2. SENSORLESS CONTROL OF A LINEAR COMPRESSOR

2.1. Operating Principle of Linear Motors

Fig. 1 (a) shows the 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). Fig. 2 shows the cross section of a linear compressor developed for refrigerators.



(a) reciprocating compressor (b) linear compressor

Fig. 1 A conventional reciprocating compressor and a linear compressor

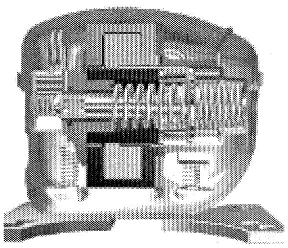


Fig. 2 Cross section of a linear compressor for refrigerators

The linear motor in a linear compressor can be controlled by adjusting the mean voltage of the applied AC voltage by using simple Triac based electronic circuits or inverter systems for better performance. The operating principle of a linear motor is shown in Fig. 3. The magnetic field grows to be maximum in a counterclockwise direction as the AC current increases to a positive peak value. (see □ of Fig. 3) 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. 3) 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. 3) Finally, the magnet reaches the rightmost as the AC current becomes zero again. (see □ of Fig. 3)

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 vibration of the magnet becomes, resulting in the larger linear speed of the piston attached to the magnet and the larger flow rate of refrigerant in a linear compressor.

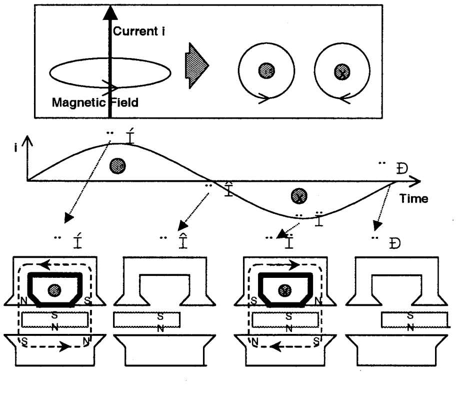


Fig. 3 Operating principle of a linear motor

As can be seen from Fig. 1 (a), the conventional reciprocating compressor uses a crank mechanism in order to change the rotational motion of motors into the linear motion. Accordingly, the reciprocating compressor can be operated safely by virtue of 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. Thus, implementation of a closed-loop control system is necessary for the accurate control of piston position. This control system 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. Hence, it is more desirable to estimate the piston position indirectly.

2.2. Sensorless Stroke Control

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 as shown in Fig. 4.[8] From the circuit model of Fig. 4, one can obtain the linear differential eq (1). The thrust force $F_e(t)$ can be expressed in eq (2).

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

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

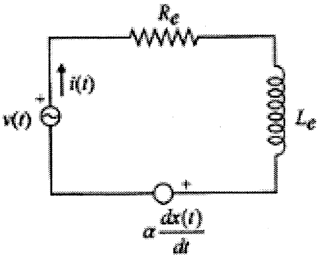


Fig. 4 Equivalent electrical circuit model of a linear motor

Since the magnetic flux density varies depending on the piston position, the motor parameters α and L_e are functions of the piston position. The effective resistance R_e is assumed to be a constant because its variance is so small as to be 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. Rearranging eq (1), one obtains

$$\frac{dx(t)}{dt} = \frac{1}{\alpha}\left(v(t) - L_e\frac{di(t)}{dt} - R_e i(t)\right) \qquad (3)$$

The estimated value of the piston position can be attained by integrating eq (3).

$$\begin{aligned}\hat{x}(t) &= \int_0^t\left(\frac{dx}{d\tau}\right)d\tau \\ &= \frac{1}{\alpha}\int_0^t\left[v(\tau) - R_e i(\tau)\right]d\tau - \frac{L_e}{\alpha}i(t) \qquad (4)\end{aligned}$$

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

$$\hat{x}(n) = \frac{T}{\alpha}\sum_{k=1}^{n}\left(\frac{v(k-1)+v(k)}{2}\right) - \frac{TR_e}{\alpha}\sum_{k=1}^{n}\left(\frac{i(k-1)+i(k)}{2}\right) - \frac{L_e}{\alpha}i(n), (n = 1,2,3,\ldots) \tag{5}$$

where T is the sampling period.

Fig. 5 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 DSP (Digital Signal Processor) CPU chips after A/D conversion. These measured variables, together with motor parameters, are used to estimate the piston position as shown in eq (5). The estimated stroke is compared with the set-point value of stroke which is determined depending on load conditions. The output of the PID controller is the set-point value of the magnitude of the applied voltage $v(t)$. The frequency of $v(t)$ is assumed to be a constant.

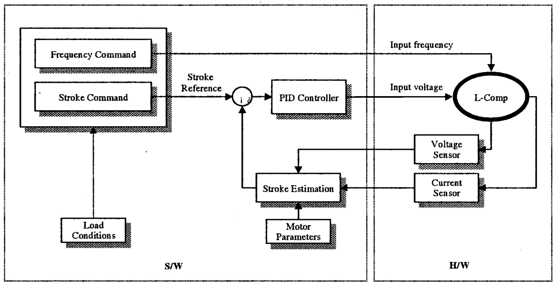


Fig. 5 Block diagram of the closed-loop sensorless stroke control system

2.3. Motor Parameters Identification

As mentioned earlier, the motor parameters vary depending on the piston position. Therefore, if one assumes that the motor parameters are constant, then the estimated piston position expressed in eq (4) (or eq (5)) will have some errors, resulting in deterioration of the dynamic performance of the closed-loop control system in Fig. 5. The motor parameters α and L_e which have substantial influence on the closed-loop control system should be identified as a function of piston position and motor current, stored in ROM table and used for an accurate estimation of piston position. From eq (3), one obtains :

$$\hat{\alpha}x(t) + \hat{L}_e i(t) = \int_0^t [v(\tau) - R_e i(\tau)]d\tau \tag{6}$$

Note that $x(t), i(t)$ and $v(t)$ in eq (6) are the measured values using a position sensor, a current sensor, and a voltage sensor, respectively. Note also that $\hat{\alpha}$ and $\hat{L}_e$ 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. Dividing t_n into n equal time intervals such as $0, t_1, t_2, \ldots, t_{n-1}, t_n$, we can get eq (7) using eq (6).

$$\begin{aligned}
\hat{\alpha}x(t_1) + \hat{L}_e i(t_1) &= \int_0^{t_1} [v(\tau) - R_e i(\tau)]d\tau \\
\hat{\alpha}x(t_2) + \hat{L}_e i(t_2) &= \int_0^{t_2} [v(\tau) - R_e i(\tau)]d\tau \\
&\vdots \\
\hat{\alpha}x(t_n) + \hat{L}_e i(t_n) &= \int_0^{t_n} [v(\tau) - R_e i(\tau)]d\tau
\end{aligned} \tag{7}$$

Rearranging eq (7) in a matrix form, we obtain :

$$A\begin{bmatrix} \hat{\alpha} \\ \hat{L}_e \end{bmatrix} = b \tag{8}$$

where n x 2 matrix A and n x 1 vector b are given as

$$A = \begin{bmatrix} x(t_1) & i(t_1) \\ x(t_2) & i(t_2) \\ \vdots & \vdots \\ x(t_n) & i(t_n) \end{bmatrix}, b = \begin{bmatrix} \int_0^{t_1} [v(\tau) - R_e i(\tau)]d\tau \\ \int_0^{t_2} [v(\tau) - R_e i(\tau)]d\tau \\ \vdots \\ \int_0^{t_n} [v(\tau) - R_e i(\tau)]d\tau \end{bmatrix} \tag{9}$$

Using pseudo inverse manipulation, one can obtain eq (10) from eq (8).

$$\begin{bmatrix} \hat{\alpha} \\ \hat{L}_e \end{bmatrix} = (A^T A)^{-1} A^T b \tag{10}$$

3. EXPERIMENTAL RESULTS

A sensorless controller for linear compressors has been implemented as shown in Fig. 6. The CPU chip was TMS320C2000 and Triac-based simple drive system was chosen for more cost-effective design. The identified motor parameters $\hat{\alpha}$ and $\hat{L}_e$ obtained using eq (10) are shown in Fig. 7 and Fig. 8, respectively. As can be seen from Fig. 7, the identified values of $\hat{\alpha}$ were approximately between 58 [Newton/Amp] and 73 [Newton/Amp] for the stroke in the range -0.008 [m]< $x(t)$ < 0.008 [m] and the current in the range -8 [Amp] $< i(t) <$ 8 [Amp]. On the other hand, one can observe from Fig. 8 that the identified values of $\hat{L}_e$ were approximately between 0.09 [H] and 0.13 [H] for the same range of the stroke and the current.

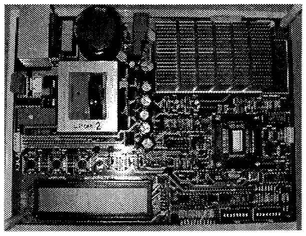
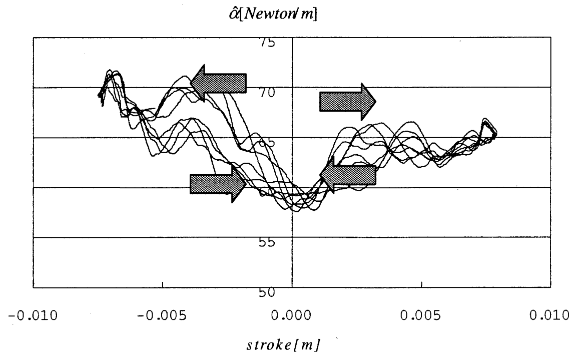
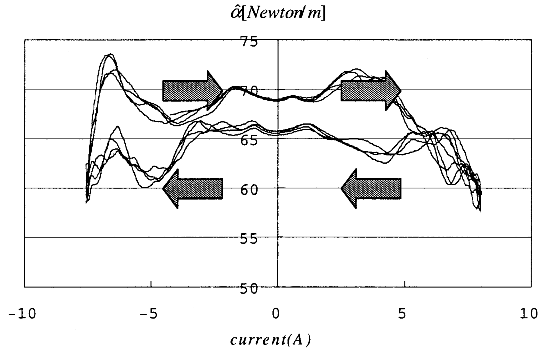


Fig. 6 Sensorless controller for linear compressors

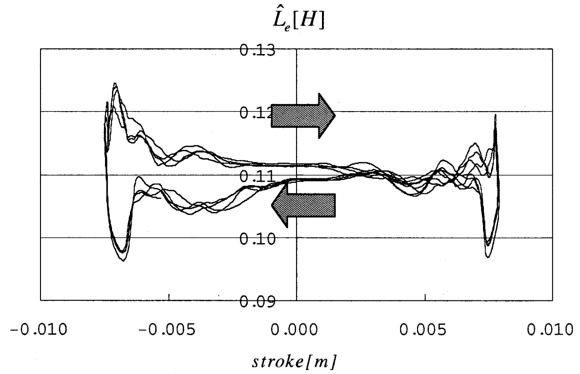


(a) Plot of $\hat{\alpha}$ as a function of stroke x

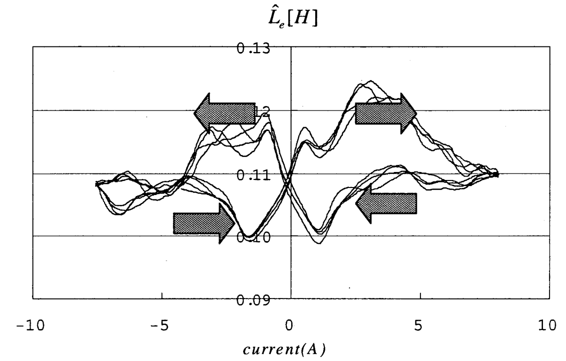


(b) Plot of $\hat{\alpha}$ as a function of current i

Fig. 7 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. 8 Experimental results for $\hat{L}_e$

Experimental results for the closed-loop stroke control system are shown in Fig. 9 for the case of using the measured stroke, the estimated stoke calculated with identified motor parameters, and the estimated stroke calculated with constant motor parameters, respectively. The stroke data were sampled 1250 times each cycle. Compared with the stroke data obtained for the case of using the measured stroke, the stroke was controlled within 2% error for the estimated stoke calculated with identified motor parameters. On the other hand, the stroke was controlled within 8% error for the estimated stroke calculated with constant motor parameters.

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. However, this method has the demerit of demanding a large memory space for storing the identified motor parameters. Therefore, in this study, a technique is proposed for solving the problem.

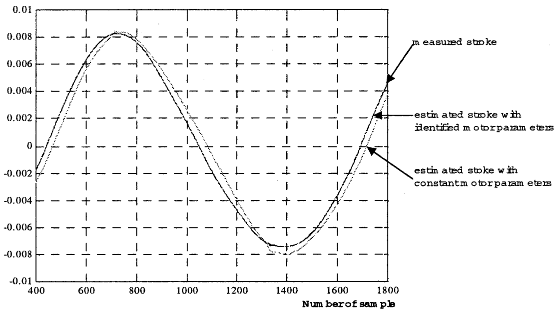


Fig. 9 Experimental results of the closed-loop stroke control system

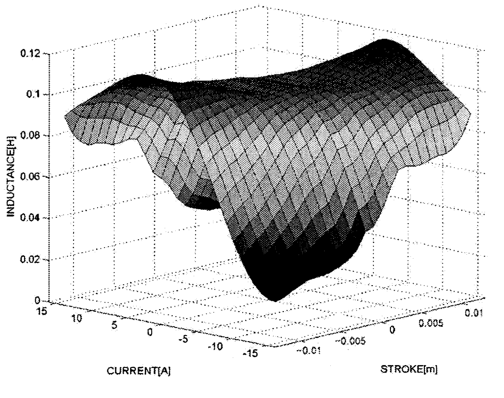


Fig. 10 3-dimensional plot of the identified inductance $\hat{L}_e$

Fig. 10 shows the 3-dimensional plot of the identified inductance $\hat{L}_e$. This plot takes the shape of a saddle. As an approach for reducing the number of identified inductance data, the identified inductance $\hat{L}_e$ in Fig. 10 was approximated to be the following 2nd-order surface :

$$S(i,x,L): L = c_0 i^2 + c_1 x^2 + c_2 ix + c_3 i + c_4 x + c_5 \qquad (11)$$

where i is the current variable, x is the stroke variable, and L is the function representing the approximated estimated inductance. Here, let n data set of the identified inductance be $\{\ (i_0, x_0, L_0)\ ,\ (i_1, x_1, L_1)\ ,\ \ldots\ (\ (i_{n-1}, x_{n-1}, L_{n-1})\ \}$. Then, one obtain

$$\begin{bmatrix} L_0 \\ L_1 \\ \vdots \\ L_{n-1} \end{bmatrix} = \begin{bmatrix} i_0^2 & x_0^2 & i_0 x_0 & i_0 & x_0 & 1 \\ i_1^2 & x_1^2 & i_1 x_1 & i_1 & x_1 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ i_{n-1}^2 & x_{n-1}^2 & i_{n-1} x_{n-1} & i_{n-1} & x_{n-1} & 1 \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \end{bmatrix} \qquad (12)$$

From this, one can obtain

$$\begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \end{bmatrix} = \begin{matrix} \textit{pseudo} \\ \textit{inverse} \\ \textit{of} \end{matrix} \begin{bmatrix} i_0^2 & x_0^2 & i_0 x_0 & i_0 & x_0 & 1 \\ i_1^2 & x_1^2 & i_1 x_1 & i_1 & x_1 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ i_{n-1}^2 & x_{n-1}^2 & i_{n-1} x_{n-1} & i_{n-1} & x_{n-1} & 1 \end{bmatrix} \begin{bmatrix} L_0 \\ L_1 \\ \vdots \\ L_{n-1} \end{bmatrix} \qquad (13)$$

Using n data set of the identified inductance given in Fig. 10, eq (13) was solved and the 3-dimensional plot, shown in Fig. 11, was finally obtained.

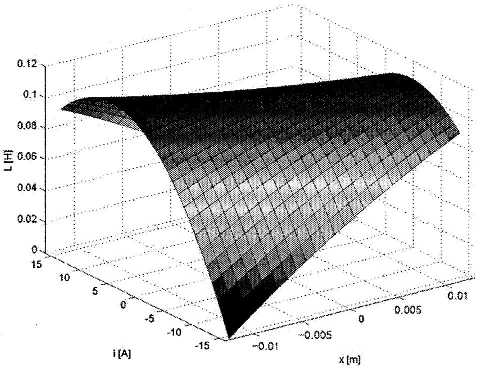


Fig. 11. 3-dimensional plot of the approximated identified inductance

This approach needs only little memory space for the approximated identified inductance. The stroke was controlled within 3.5% error for the estimated stoke calculated with approximated identified motor parameters compared with the case of using the measured stroke.

4. CONCLUSIONS

A closed-loop sensorless stroke control system for a linear compressor has been designed. The motor parameters were identified as a function of the piston position and the motor current, stored in ROM table, were used for an accurate estimation of piston position later. Experimental studies have demonstrated that an approximation of the identified motor parameters were practical for sensorless stroke control of a linear compressor.

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