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Dynamic Performance Improvement of Oscillating Linear Motors via Efficient Parameter Identification

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Abstract

In this paper, the dynamic performance of oscillating linear motors, which are used in household refrigerators, is improved by means of efficient parameter identification. Oscillating linear motor parameters are identified as a function of the piston position and the motor current. They are stored in a ROM table and used later for an accurate estimation of piston position. The identified motor parameters are also approximated to the 2^{nd}-order surface functions, which are divided into 2 or 4 subsections in order to decrease identification errors. Experimental results are given to show that the proposed control scheme can provide oscillating linear motors with high dynamic performance.

Key Words: Identified motor parameters, Oscillating linear motor, Piston position, Surface function

I. INTRODUCTION

Many countries such as the U.S., the EU, and Japan have some kind of energy regulation programs to decrease the energy consumption of electric home appliances. In a house, a refrigerator consumes about 30% of the total electric energy and the compressor which circulates the refrigerant through the refrigeration system consumes most of the electric energy in a refrigerator. Hence, energy efficient compressors are essential to the saving of household electric energy. A linear compressor has an oscillating linear motor coupled to a resonating mechanical system: a piston and a spring. The advantages of this compressor when compared to a standard reciprocating compressor are a high reduction of energy losses and a variable cooling capacity. 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].

One of the major advantages of a linear compressor is that it is oil-free. The lubrication is provided by gas bearings on the cylinder wall and a piston support mechanism which allows contact free oscillation of the piston. This enables usage with refrigerants which would degrade over time due to contact with oil. It also provides extremely quiet long life operation. Furthermore, the amplitude of the oscillation and the mean position of the piston can be controlled allowing the refrigeration system to maintain a high coefficient of performance (COP) under partial load conditions.

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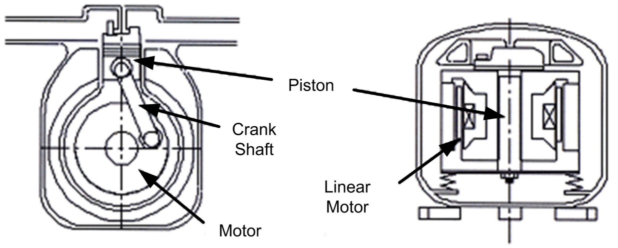
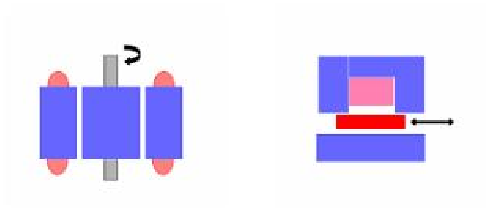
It has been shown that linear compressors have extremely low friction losses compared to other compressor types and that a high efficiency can be achieved for a variety of refrigerants and compressor sizes [1]. The problems associated with linear motor configurations which are potentially applicable to linear compressors have been discussed [2]. They described moving coil type and moving magnet type linear motors and two methods of linear compressor control that have been successfully applied. Some non-refrigeration applications for linear compressors have also beem 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 and medical cooling [4]. The piston positioning accuracy and the efficiency of a sensorless linear compressor system with a linear pulse motor were examined using analytical and experimental approaches [5]. However, the motor parameters were not identified fully. A dual stroke and phase control system was proposed for the linear compressors of a split-stirling cryocooler [6]. A linear compressor was developed for a 680 liter household refrigerator [7]. It reduced the energy consumption of a refrigerator by 47% when 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 are identified as a function of the piston position and the motor current. These parameters are stored in a ROM table and used later for an accurate estimation of piston position. The identified motor parameters are approximated to the 2^{nd}-order surface functions in order to decrease memory size. They can also be divided into 2 or 4 subsections to decrease identification



(a) reciprocating compressor (b) linear compressor

Fig. 1. Conventional reciprocating compressor and linear compressor.



(a) reciprocating motor (b) linear motor

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

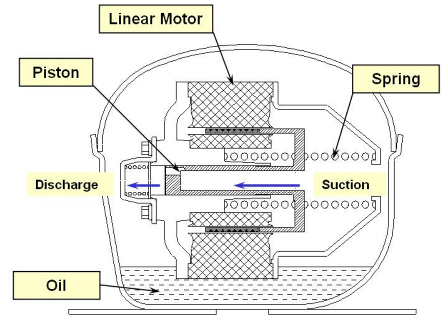


Fig. 3. A cross-section view of a linear compressor for refrigerators.

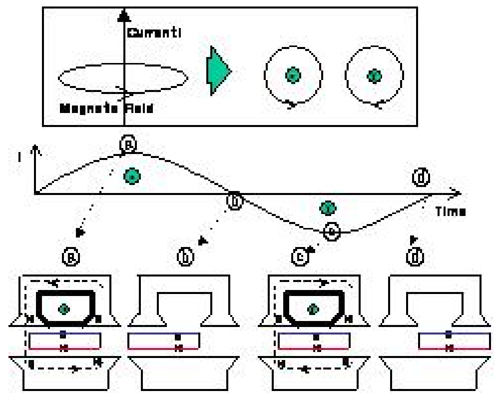


Fig. 4. Operating principle of an oscillating linear motor.

errors. Experimental results have been obtained in order to show the feasibility of the proposed control scheme for linear compressors.

II. Sensorless Control of an Oscillating Linear Motor

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.

Fig. 2(a) shows that the motor which was chosen for a conventional reciprocating compressor rotates. On the other hand, the oscillating linear motor chosen for a linear compressor moves linearly as can be seen in Fig. 2(b). Fig. 3 shows a cross-sectional view of a linear compressor developed for refrigerators.

The operating principles of an oscillating linear motor are shown in Fig. 4. The magnetic field grows to its maximum in a counterclockwise direction as the AC current increases to a positive peak value (see ⓐ of Fig. 4). 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. 4). 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. 4). Finally, the magnet reaches the rightmost position as the AC current becomes zero again (see ⓓ of Fig. 4).

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.

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.

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 as shown in Fig. 5 [8]. From this circuit model, one can obtain the linear differential

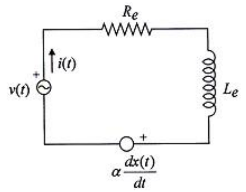


Fig. 5. Equivalent electrical circuit model of a linear motor.

eq (1). The thrust force $F_e(t)$ can be expressed in eq (2).

$$\alpha \frac{dx(t)}{dt} + L_e \frac{di(t)}{dt} + R_e i(t) = v(t) \quad (1)$$
$$F_e(t) = \alpha i(t) \quad (2)$$

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:

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

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

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

Fig. 6 shows the block diagram of a closed-loop sensorless stroke control system for linear compressors. The applied voltage $v(t)$ and the motor current $i(t)$ are measured and input to the DSP (digital signal processor) CPU chips after A/D conversion. These measured variables, together with the motor parameters, are used to estimate the piston position as shown in eq (4). The estimated stroke is compared with the set-point value of the stroke which is determined depending on the 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.

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) will have some errors. This will result in a deterioration of the dynamic performance of the closed-loop control system in Fig. 6. The motor parameters α and L_e which have substantial influence on the closed-loop control system should be identified as a function of the piston position and motor current, stored in a ROM table and used for an accurate estimation of piston position. From eq (3), one obtains:

$$\hat{\alpha} x(t) + \hat{L}_e i(t) = \int_0^t [v(\tau) - R_e i(\tau)] d\tau \quad (5)$$

Note that $x(t)$, $i(t)$ and $v(t)$ in eq (5) 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 the time period of the piston moving linearly in the steady state. Dividing t_n into *n* equals time intervals such as $0, t_1, t_2, \ldots, t_{n-1}, t_n$. We can get eq (6) using eq (5).

$$\begin{aligned}\hat{\alpha}(t_1) + \hat{L}_e(t_1) &= \int_0^{t1} [v(\tau) - R_e i(\tau)] d\tau \\ \hat{\alpha}(t_2) + \hat{L}_e(t_2) &= \int_0^{t2} [v(\tau) - R_e i(\tau)] d\tau \\ &\vdots \\ \hat{\alpha}(t_n) + \hat{L}_e(t_n) &= \int_0^{tn} [v(\tau) - R_e i(\tau)] d\tau\end{aligned} \quad (6)$$

Rearranging eq (6) in a matrix form, we obtain :

$$A \begin{bmatrix}\hat{\alpha} \\ \hat{L}_e\end{bmatrix} = b \quad (7)$$

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

$$A = \begin{bmatrix} x(t_1) & i(t_1) \\ x(t_2) & i(t_2) \\ \vdots & \vdots \\ x(t_n) & i(t_n)\end{bmatrix}, \; b = \begin{bmatrix}\int_0^{t1}[v(\tau) - R_e i(\tau)]d\tau \\ \int_0^{t2}[v(\tau) - R_e i(\tau)]d\tau \\ \vdots \\ \int_0^{tn}[v(\tau) - R_e i(\tau)]d\tau\end{bmatrix} \quad (8)$$

Using pseudo inverse manipulation, one can obtain eq (9) from eq (7).

$$\begin{bmatrix}\hat{\alpha} \\ \hat{L}_e\end{bmatrix} = (A^T A)^{-1} A^T b \quad (9)$$

III. Experimental Results

A sensorless controller for linear compressors has been implemented as shown in Fig. 7. The CPU chip was a TMS320C2000 and a Triac-based simple drive system was chosen for a more cost-effective design. For the experimental study, we chose a 2.2kW linear compressor as shown in Table 1. This compressor was developed for application to air conditioners. We also set up an experimental apparatus for performance evaluation of the sensorless controller as shown in Fig. 8. The set-point value of the stroke was 16mm. The frequency of the voltage was set to be 60Hz.

At first, the motor parameters are assumed to be constant. Then, the dynamic performance of the closed-loop sensorless stroke control system, shown in Fig. 6, is evaluated for various loads. Fig. 9 shows the experimental results for various load changes. The waveforms of the motor voltage and current are shown in Fig. 10. As the load increased, the stroke command changed from 14mm to 15mm and then to 16mm. At the same time, we changed the PD (compressor discharge pressure) and the PS (compressor suction pressure) for various load tests. We found that our compressor could be controlled with some errors for various loads.

The identified motor parameters $\hat{\alpha}$ and $\hat{L}_e$ obtained using eq (9) are shown in Fig. 11 and 12, respectively. As can be seen from Fig. 11, the identified values of $\hat{\alpha}$ were approximately between 30 [Newton/Amp] and 55 [Newton/Amp] for the stroke in the range -0.01 [m]$< x(t) <$ 0.01 [m] and the current in the range -10 [Amp] $< i(t) <$ 10 [Amp].

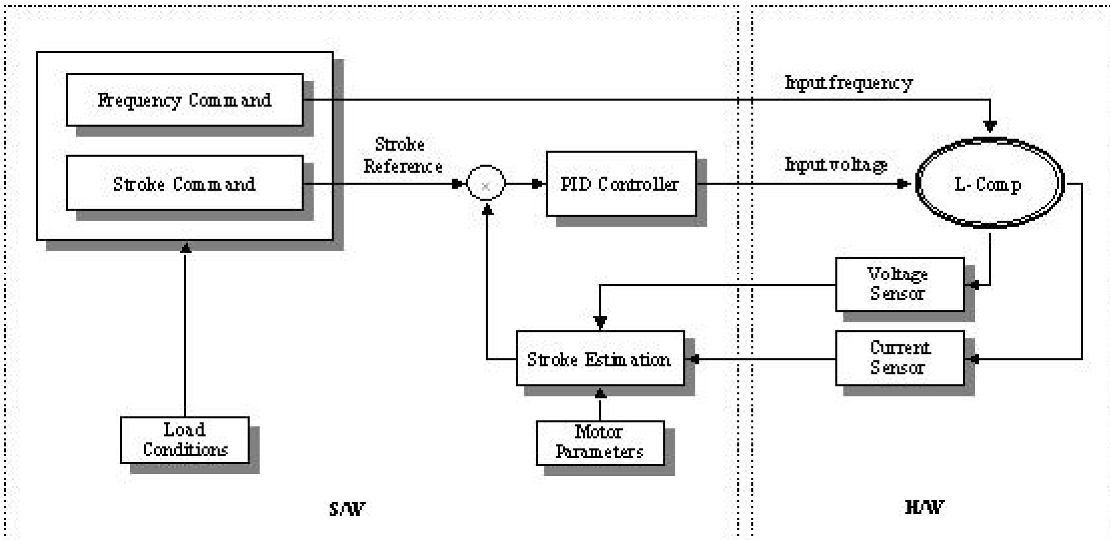


Fig. 6. Block diagram of the closed-loop sensorless stroke control system.

Fig. 7. Sensorless controller for linear compressors.

TABLE I
LINEAR MOTOR SPECIFICATIONS

Rated output power	2.2 kW
Rated voltage	220 Vrms
Rated current	7 Arms
Rated stroke	20 mm
Voltage frequency	60 Hz
R_e	2.5 Ω
α	66 Newton/Amp
L_e	0.11 H

Fig. 8. Experimental apparatus set up for sensorless controller evaluation.

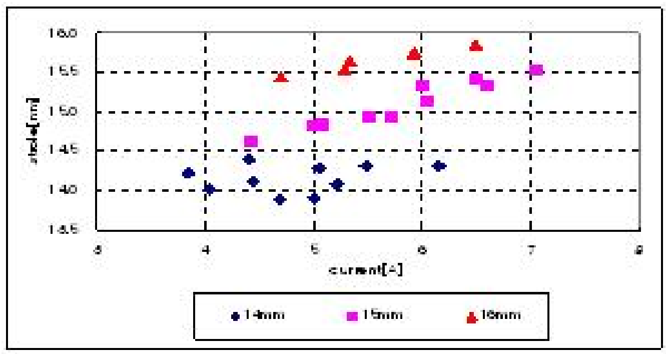
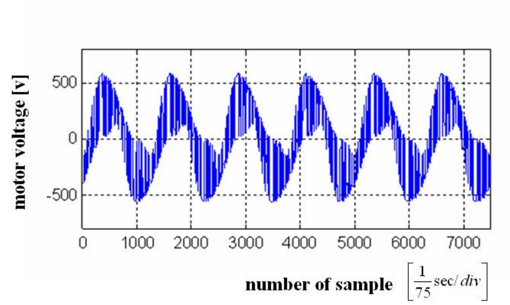
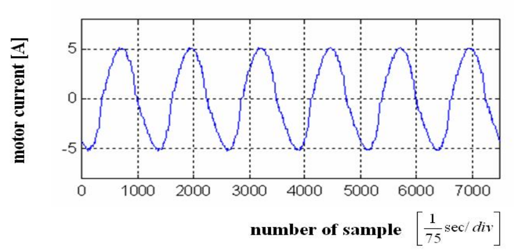


Fig. 9. Experimental results for load changes.



(a) Waveforms of motor voltage



(b) Waveforms of motor current

Fig. 10. Waveforms of motor voltage and current.

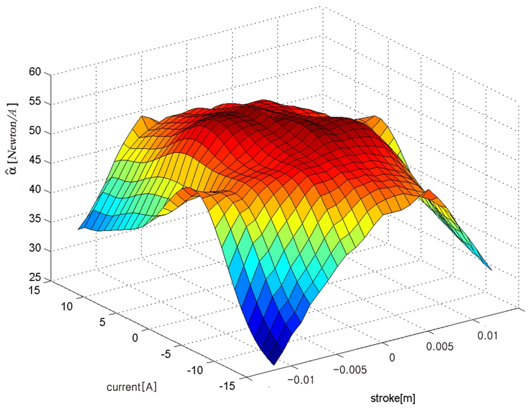


Fig. 11. 3-dimensional plot of the identified force constant $\hat{\alpha}$.

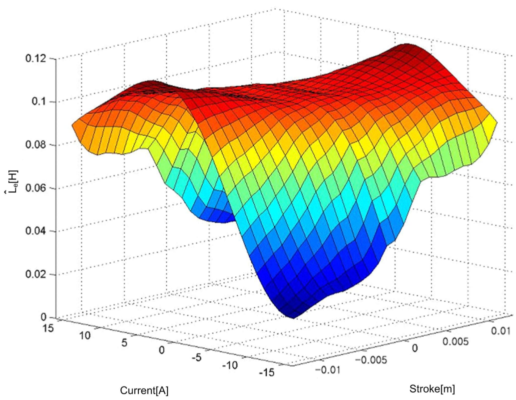


Fig. 12. 3-dimensional plot of the identified inductance $\hat{L}_e$.

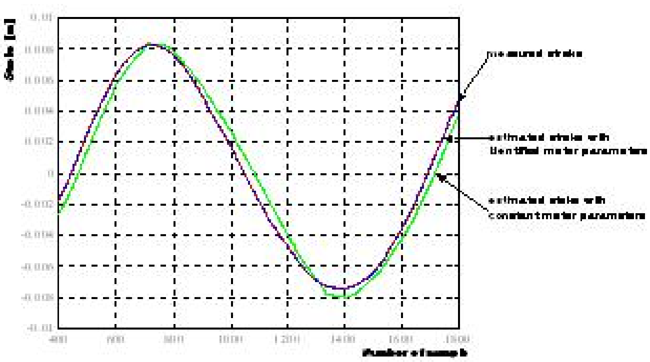


Fig. 13. Experimental results of the closed-loop stroke control system.

One can observe from Fig. 12 that the identified values of $\hat{L}_e$ were approximately between 0.03 [H] and 0.12 [H] for the same ranges of the stroke and the current. The identified motor parameters shown in Fig. 11 and 12 can be stored in the ROM table and may be used later for the stroke estimation in eq (4).

Experimental results for the closed-loop stroke control system are shown in Fig. 13 and 14 for the case of using the measured stroke, the estimated stoke calculated with the identified motor parameters and the estimated stroke calculated with the constant motor parameters, respectively. The stroke

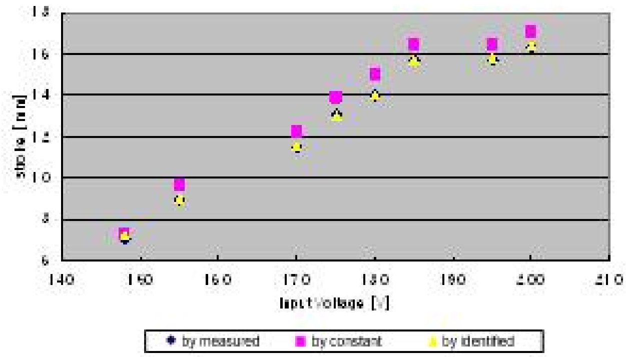


Fig. 14. Stroke results for measured, constant, and identified motor parameters.

data were sampled 1250 times per cycle. Here, the measured stroke means that the piston $x(t)$ was measured using a LVDT sensor. On the other hand, the estimated stoke calculated with the identified motor parameters means that the identified motor parameters shown in Fig. 11 and 12 are used in eq (4) and that the piston $x(t)$ is estimated using eq (4). Finally, the estimated stroke calculated with the constant motor parameters means that the motor parameters in eq (4) are assumed to be constant and that the piston $x(t)$ is estimated using eq (4). It is very difficult to get exact information on piston position, so we assume that the measured stroke is correct and that it has no errors.

Compared with the stroke data obtained using the measured stroke, the stroke was controlled within a 2% error for the estimated stoke calculated with the identified motor parameters. On the other hand, the stroke was controlled within an 8% error for the estimated stroke calculated with the constant motor parameters.

Up to now, it has been costly and difficult to install a position sensor for measuring stroke. It has also been found that the estimated stroke calculated with constant motor parameters generates substantial errors. On the other hand, the estimated stroke calculated with identified motor parameters generated fewer errors. However, this method has the disadvantage of demanding a large memory space for storing the identified motor parameters. Therefore, in this study, a technique is proposed for solving this problem.

As an approach for reducing the amount of identified inductance data, the identified inductance $\hat{L}_e$ in Fig. 12 was approximated to be the following 2nd-order surface:

$$S(i,x,L) : L = c_0 i^2 + c_1 x^2 + c_2 ix + c_3 i + c_4 x + c_5 \quad (10)$$

where i is the current variable, x is the stroke variable and L is a function representing the approximated estimated inductance. Here, let the 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,

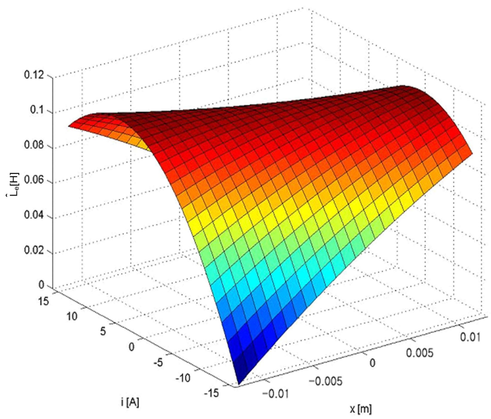


Fig. 15. The 2nd order approximation of $\hat{L}_e$.

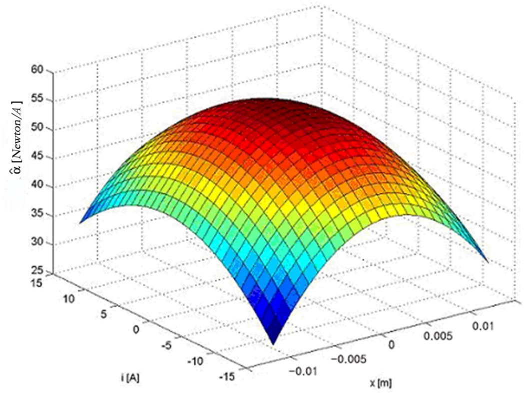


Fig. 16. The 2nd order approximation of $\hat{\alpha}$.

one can obtain:

$$\begin{bmatrix} L_0 \\ L_1 \\ \vdots \\ L_{n-1} \end{bmatrix} = \begin{bmatrix} i_0^2 & x_0^2 & i_0x_0 & i_0 & x_0 & 1 \\ i_1^2 & x_1^2 & i_1x_1 & i_1 & x_1 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ i_{n-1}^2 & x_{n-1}^2 & i_{n-1}x_{n-1} & i_{n-1} & x_{n-1} & 1 \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \end{bmatrix} \quad (11)$$

From this, one can obtain:

$$\begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \end{bmatrix} = \begin{matrix} \textit{pseudo} \\ \textit{inverse} \\ \textit{of} \end{matrix}$$

$$\begin{bmatrix} i_0^2 & x_0^2 & i_0x_0 & i_0 & x_0 & 1 \\ i_1^2 & x_1^2 & i_1x_1 & i_1 & x_1 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ i_{n-1}^2 & x_{n-1}^2 & i_{n-1}x_{n-1} & i_{n-1} & x_{n-1} & 1 \end{bmatrix} \begin{bmatrix} L_0 \\ L_1 \\ \vdots \\ L_{n-1} \end{bmatrix} \quad (12)$$

Using the n data set of the identified inductance $\hat{L}_e$ given in Fig. 12, eq (12) was solved and the 3-dimensional plot, shown in Fig. 15, was finally obtained. Similarly, using the n data of the identified force constant $\hat{\alpha}$ given in Fig. 11, the 2nd order approximation, shown in Fig. 16, was also obtained. This approach needs little memory space. Only the information $C_i (i = 0, 1, \ldots, 5)$ is needed and the motor parameters are calculated using eq (10). In this case, the stroke was controlled within a 3.0% error.

Next, in order to decrease the approximation errors, the identified motor parameters are divided into 2 parts and are approximated individually as shown in Fig. 17. In this case, we found that the stroke was controlled within a 2.8% error. Fig. 18 shows the case of division into 4 parts, which gave a 2.6% error for the stroke control.

Up to now, it has been found that the estimated stroke calculated with the constant motor parameters generated substantial errors. On the other hand, the estimated stroke calculated with the identified motor parameters generated comparatively few errors.

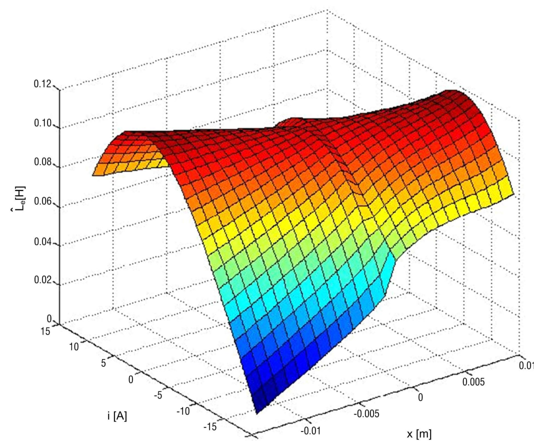


Fig. 17. The division into 2 parts and approximation of $\hat{L}_e$.

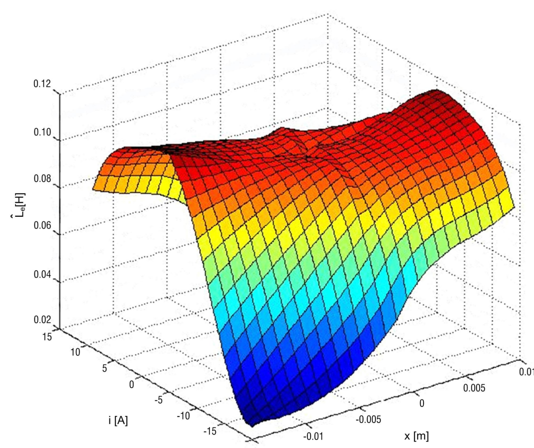


Fig. 18. The division into 4 parts and approximation of $\hat{L}_e$.

IV. Conclusions

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. Then, they are stored in a ROM table and used later for an accurate estimation of the piston position. The identified motor parameters are also approximated to the 2nd-order surface functions, which are then divided into 2 or 4 subsections in order to decrease identification errors. Experimental studies have demonstrated that the identified motor parameters are practical for sensorless stroke control of a linear compressor.

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