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## New Capacity Modulation Algorithm for Linear Compressor

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### ABSTRACT

Recently, due to its high efficiency, linear compressors with a free piston have attracted wide attention to the manufacturers of refrigerators and freezers. Linear compressors have many notable different characteristics compared to BLDC reciprocating compressors, such as mechanism, motor configuration, and control method. The cooling capacity of a BLDC reciprocating compressor can be changed by the motor speed variation, but a linear compressor controls the piston stroke to modulate the compression volume on which depends the cooling capacity at a fixed excitation frequency. In this paper, a new cooling capacity modulation technique applied to linear compressors is proposed. It has a unique load-adaptive control function so that it helps linear compressors keep automatically driven at the optimal efficiency condition regarding the heat load of the refrigerator. The performance improvement using the suggested control algorithm is verified and compared to the quality of BLDC reciprocating compressors through simulation and experimental results.

### 1. INTRODUCTION

A conventional reciprocating compressor utilizes a crank-shaft mechanism to convert the rotational motion of the motor into the oscillating motion to drive a piston of the compressor. The efficiency of the rotary compressor is low, because it has large mechanical losses due to the crank-shaft mechanism. On the other hand, the linear compressor has higher efficiency by reducing the mechanical losses due to the crank mechanism and has been developed as a mechanism for the compressing of expended refrigerant gas in a cooling apparatus such as a refrigerator.

Recently, not only the efficiency of the compressor, but also the cycle efficiency of the refrigerator gets more important in a total refrigerator system efficiency point of view. In order to enhance the cycle efficiency of a refrigerator, cooling capacity modulation of the compressor is required, but the modulation technique of linear compressors is different from that of BLDC reciprocating compressors. The cooling capacity of a linear compressor is modulated by adjusting the stroke of the piston, while a BLDC reciprocating compressor is controlled by the rotational speed of the motor.

In this paper, a new cooling capacity modulation algorithm, which regulates the cooling capacity of the linear compressor near the optimal efficiency point according to load variation, is proposed. A stroke estimation method using motor voltage and current without displacement sensor is introduced and a unique load detection technique needed for driving the compressor at the optimal efficiency point is suggested. The cycle loss of linear compressors and that of BLDC reciprocating compressors with load variations are investigated. The experimental results are carried out in order to verify the performance of the proposed linear compressor control system.

### 2. SYSTEM MODELS

The model of a linear compressor is expressed as a mechanical equation from mechanical structure and electric equation from circuit configuration.

## 2.1 Mechanical Structure

Figure 1 shows that the linear compressor consists of motor coil, magnets, piston, cylinder, discharge and suction valves, several springs, and so on. Excitation current drives a linear motor to oscillate the piston supported by mechanical springs, and the valves are open and close automatically due to the pressure difference of compressed refrigerant. The mechanical equation for linear compressor can be simply expressed as following:

$$m\ddot{x} + c\dot{x} + kx = \alpha i \quad (1)$$

where

$m$  : effective piston moving mass [kg]

$c$  : damping coefficient [N sec/m]

$k$  :  $k_m + k_g$

$k_m$  : mechanical spring constant [N/m<sup>2</sup>]

$k_g$  : gas spring constant [N/m<sup>2</sup>]

$i$  : motor current [A]

$x$  : stroke of piston [m]

$\dot{x}$  : velocity of piston [m/sec]

$\ddot{x}$  : acceleration of piston [m/sec<sup>2</sup>]

$\alpha$  : motor constant [N/A].

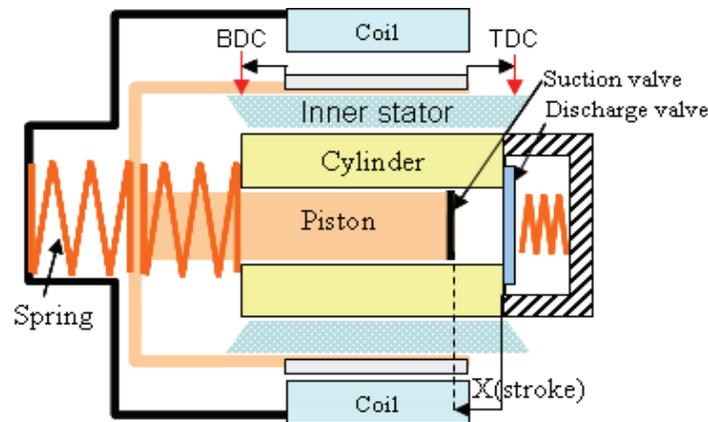


Figure 1 Structure diagram of a linear compressor

## 2.2 Circuit Configuration

In order to drive a linear compressor, the linear motor whose equivalent circuit diagram is shown in Fig. 2 is controlled using a PWM inverter. The PWM inverter generates a pulse wave to drive the linear motor which can be represented by resistance, inductance, and EMF proportional to the velocity of the piston.

From Fig. 2, the output voltage of the PWM inverter can be written as following:

$$V_M = Ri + L \frac{di}{dt} + \alpha \dot{x} \quad (2)$$

where

$R$  : resistance [ $\Omega$ ]

$L$  : inductance [H]

$V_M$  : motor voltage [V].

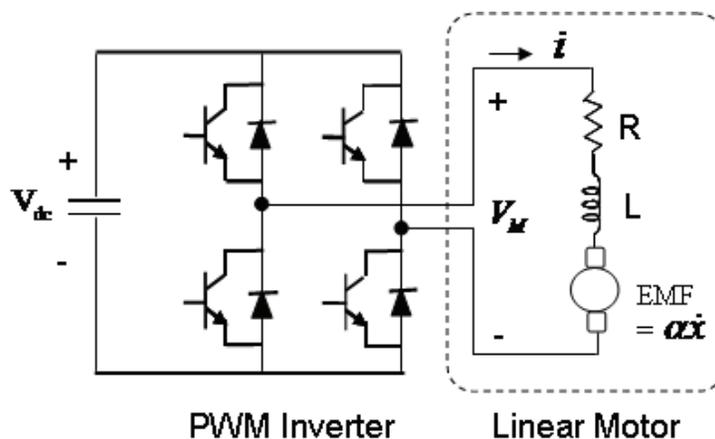


Figure 2 Single phase PWM inverter feeding linear motor

### 3. CAPACITY MODULATION TECHNIQUE IN THE LINEAR COMPRESSOR

#### 3.1 Stroke estimation

For the linear compressor system, an accurate control of the piston stroke is essential to regulate the cooling capacity which is needed for a refrigerator. A displacement sensor can be used to obtain the position information, but a stroke estimation method without any extra sensor is adopted due to severe environments such as cable connection problems, high temperature, and high pressure in a hermetic compressor.

The stroke estimation can be inspired by the electric equation, Eq. (2), including EMF, as

$$x = \frac{1}{\alpha} \left\{ \int (V_M - Ri) dt - Li \right\}. \quad (3)$$

Equation (3) shows that the displacement of the piston is related to motor voltage, current and motor constants such as alpha, resistance, and Inductance. The piston stroke calculated from Eq. (3) is used for the cooling capacity modulation of the linear compressor.

#### 3.2 Load detection

In the normal operation of a refrigerator, the cooling capacity should be varied according to the heat load. So, it is very important to figure its heat load out when the controller of a refrigerator commands the cooling capacity level of the compressor. A linear compressor has the advantage to be able to estimate its load by itself in contrast with a BLDC reciprocating compressor. The piston stroke of a linear compressor, the current related to the load, and the phase difference between the waveform of stroke and current can be derived from the mechanical equation, Eq. (1). The experimental results of them are shown in Fig. 3, where the heat load of the refrigerator can be represented by the room temperature (RT) since high room temperature enlarges the phase difference between the stroke and current proportionally.

Therefore, it is reasonable to use the phase difference between the piston stroke and the motor current as an indicator of the strength of heat load. As a result, it is possible to modulate the cooling capacity of linear compressor along the heating load of refrigerator with the phase difference.

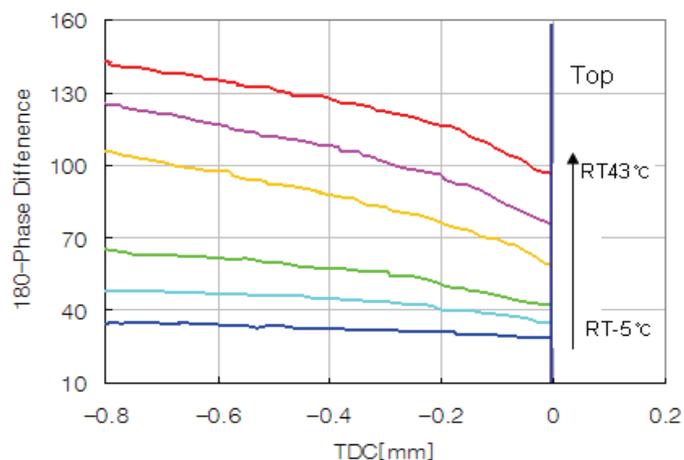


Figure 3 Phase difference between the current and the stroke according to load variation

### 3.3 Capacity modulation of linear compressor

In a refrigerator system, cooling capacity modulation is required to enhance the cycle efficiency. A typical BLDC reciprocating compressor obtains the modulated cooling capacity by changing the running frequency. On the contrary, a linear compressor modulates the cooling capacity by varying the length of stroke as shown in Fig.4. When the load is light, a linear compressor should generate a small cooling capacity. So, it is driven by a small length of stroke. When the load is heavy, a linear compressor should produce a large cooling capacity. So, it is driven by a full length of stroke.

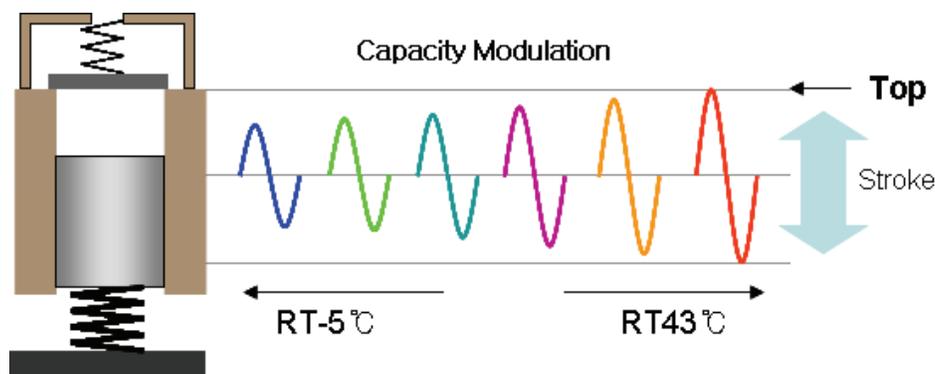


Figure 4 Piston stroke according to load variation

## 4. EXPERIMENTAL RESULTS

The power IGBT single-phase voltage fed inverter and linear compressor for the refrigerator are available for experimental study. The control system is implemented by 32bit MN103SC2D microprocessor operating with a clock frequency of 40MHz. Figure 5 shows that the stroke of the piston and the input power is decreasing according to the load A, B, and C. The load of A, to get the fresh food compartment cool, is heavier than that of B; and the load of B for the freezer heavier than that of C, at pump down.

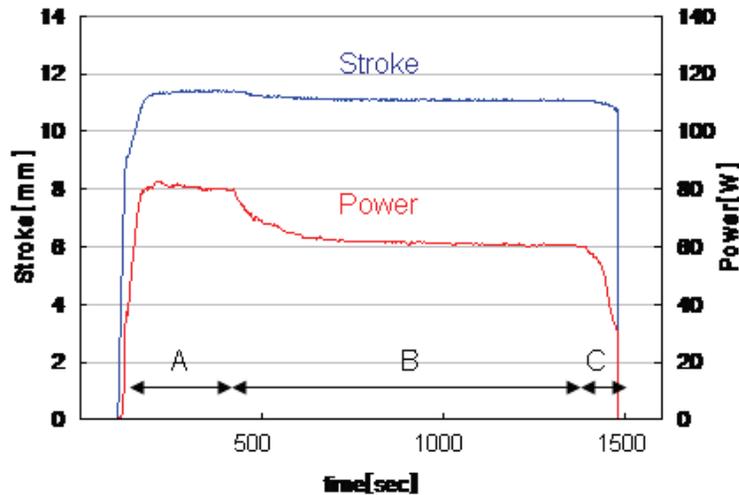


Figure 5 Stroke and power modulation according to load variation

The cooling capacity of the linear compressor is modulated by adjusting the stroke of the piston through load detection by itself, while that of the BLDC reciprocating compressor is modulated by changing the frequency of the piston from a refrigerator reference. Figure 6 and 7 show the cycle loss of a BLDC reciprocating compressor and a linear compressor respectively, while the cooling capacity is modulated under each load condition. If the driving point is larger than the heat load curve, the cooling capacity of the compressor is higher than the cooling capacity needed for a refrigerator. On the other hand, if the driving point is smaller than the heat load curve, the cooling capacity of the compressor is lower than the cooling capacity needed for a refrigerator. The cycle efficiency is the highest on the heat load curve. As a result, Figure 6 and 7 show that the cycle loss of the linear compressor is less than that of the BLDC reciprocating compressor, after the automatic load adaptive control algorithm is applied to the linear compressor.

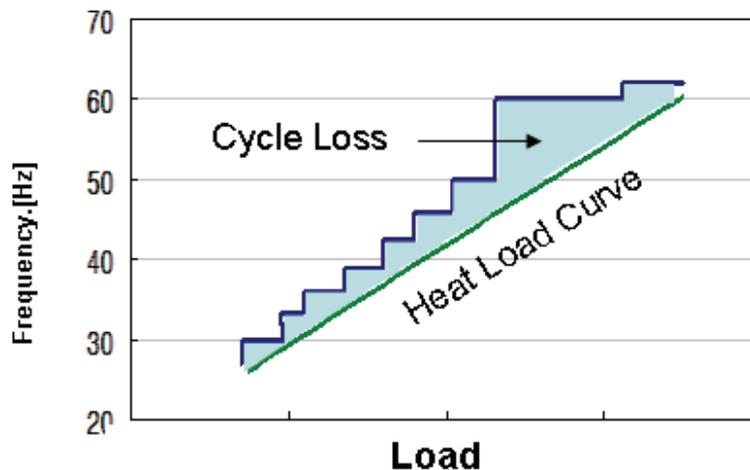


Figure 6 Capacity modulation of a BLDC reciprocating compressor according to load variation

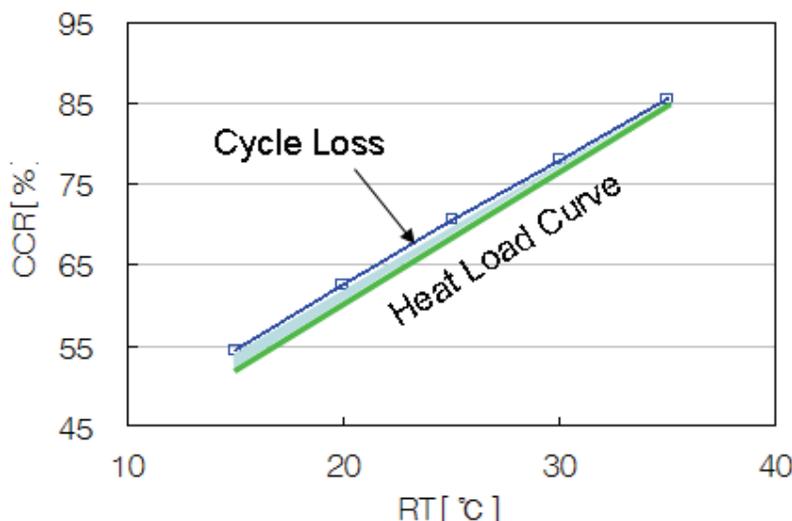


Figure 7 Capacity modulation of a linear compressor according to load variation  
(RT : room temperature, CCR : cooling capacity ratio)

## 5. CONCLUSIONS

In this paper, a new capacity modulation algorithm for the linear compressor is proposed, and its effect is verified through experimental results compared to the case of the BLDC reciprocating compressor. The proposed algorithm is a unique technology of linear compressors, which detects the load condition from the phase difference between the current and the stroke and then regulates the cooling capacity required for a refrigerator under each load condition. The cycle efficiency turns to be the maximum when the compressor is operated along the heat load curve of a refrigerator regardless of the load condition. It is possible to control the cooling capacity continuously using the linear compressor with the proposed algorithm.

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