

Experimental and Theoretical Investigation of Nonlinear Dynamic characteristics in an Oil-free Moving Coil Linear Compressor

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Abstract. The gas pressure, piston displacement and current response characteristics of an oil-free moving coil linear compressor driven by sinusoidal voltages at different frequencies have been experimentally studied. The results show that the response curves of gas pressure, piston displacement and current have nonlinear distortions deviating from the sinusoidal waveform. Among them, the piston displacement waveform has relatively small deviation from sinusoid, and the total harmonic distortion rate (THD) of piston displacement has a maximum value of 6.2% at 50Hz; the current waveform has relatively large deviation from sinusoid, and the THD of current has a maximum value of 73.7% at 60Hz. At this time, the current has two peaks in one cycle. It was analyzed that the nonlinear distortion of displacement and current occurs only in the compression process in a working cycle. In addition, a nonlinear dynamic model based on MATLAB software was established to analyze current distortion. The simulated values of gas pressure, piston displacement and current curves have a good coincidence with measured values. Finally, it is present that the severe distortion of the current curve is mainly caused by the non-linearity of the gas pressure.

1. Introduction

Vapor compression refrigeration (VCR) is a very effective way for electronic cooling. As the core component of the VCR system, the compressor directly affects the energy efficiency ratio (EER) of the system. Liang et al. (2014) ^[1] pointed out that linear compressors have great potential for electronic cooling because of their unique structural advantages compared to conventional compressors. The linear compressor uses a linear oscillation motor to directly drive the piston, which simplifies the



transmission mechanism, eliminates/reduces the lateral force between the cylinder and the piston and greatly improves the mechanical efficiency; resonance operation effectively amplifies the piston stroke; the use of large radial-axial stiffness ratio mechanical springs ensures that the piston does not touch the cylinder wall surface and avoids the use of lubricant. Oil-free operation improves the heat transfer performance of heat exchangers, widens the choice of refrigerants and simplifies the refrigeration system. In addition, the clearance and stroke of the linear compressor are adjustable, and the cooling capacity can be easily adjusted according to actual thermal loads (Kim and Kim (2014))^[2].

The gas pressure of linear compressors is non-linear (non-sinusoidal); its piston is free and the piston offset changes with operating conditions; these characteristics increase the difficulty of studying non-linear gas pressure. Thus, a number of research are conducted to focus on the nonlinear dynamics of linear compressors. Schmidt (1956)^[3] first proposed the idea of simplifying non-linear gas force into a damping and a spring; Kim et al. (2009)^[4] linearized the gas force using the average method; Choi and Kim (2000)^[5] proposed the Fourier method to linearize the gas force; Liang (2018)^[6] presents a method to calculate gas spring stiffness at high pressure ratios; Zou et al. (2018)^[7] proposed an online method for measuring gas spring stiffness based on vector graphics. In experimental measurements, Tang (2010)^[8] installed a force sensor between the motor bearing and the compressor piston to measure the gas force; Li et al. (2019)^[9] installed a high-frequency pressure sensor in the cylinder wall to directly measure the gas pressure in the compression chamber

From the literature survey, it is clear that a lot of studies have investigated on non-linear gas force by experimental testing and theoretical modelling. However, there is a lack of research on the nonlinear response characteristics of linear compressors driven by sinusoidal voltage. In order to study the issue, the gas pressure in the compression chamber (the gas pressure), piston displacement and current response curves of a moving coil linear compressor driven by sinusoidal voltages were measured simultaneously. A nonlinear dynamic model was established and the gas pressure, piston displacement and current curves by simulation were compared with the measured curves.

2. Nonlinear Dynamic Modeling of Linear Compressor

Figure 1 shows a schematic diagram of the simplified dynamic model. The electrical model is simplified as a resistance-inductance-motor structure, and the mechanical model is simplified as a mass-spring-damper structure.

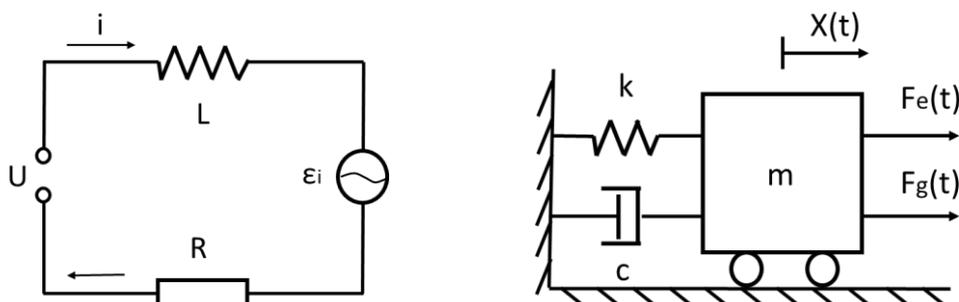


Figure 1. Dynamic model. (a) Electrical model. (b) Mechanical model.

The equations are listed as follows:

$$Ri + L \frac{di}{dt} + K_e i = U \quad (1)$$

$$m \frac{d^2x}{dt^2} + c \frac{dx}{dt} + k_s x = k_e i + F_g \tag{2}$$

Where i is the current, R is the resistance, L is the inductance, k_e is the electromagnetic force coefficient, U is the driving voltage; x is the piston displacement, m is the total moving mass, c is the damping coefficient, k_s is the mechanical spring coefficient, and F_g is the gas force.

The gas force can be expressed in the following:

$$F_g(t) = [P_c(t) - P_s] A_p \tag{3}$$

Where P_c is the gas pressure in the compression chamber, P_s is the suction pressure, and A_p is the cross-sectional area of the piston.

Figure2. reflects the working process of the compression chamber. The compression process and the expansion process was treated as polytropic processes, and suction and exhaust valves are treated as ideal valves without pressure loss. Thus the instantaneous gas pressure in the compression chamber can be obtained. The instantaneous pressure P_c of the compression chamber is:

$$P_c(t) = \begin{cases} \left[\frac{x_0 + X}{x_0 - x(t)} \right]^n P_s & \text{compression process} \\ P_d & \text{exhaust process} \\ \left[\frac{x_0 - X}{x_0 - x(t)} \right]^n P_d & \text{expansion process} \\ P_s & \text{suction process} \end{cases}$$

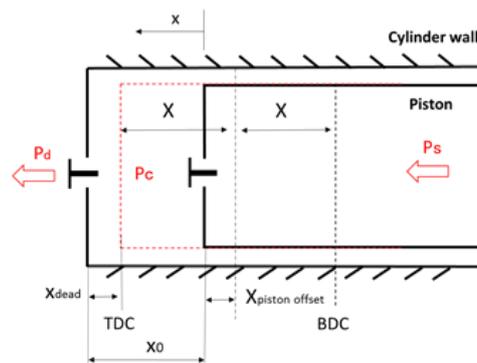


Figure 2. Compression chamber diagram

where x_0 is the initial clearance length, X is half the stroke and n is the polytropic index

3 Experimental Setup

3.1 Test system

Figure3. is a schematic diagram of a VCR system driven by a linear compressor. The system consists of a linear compressor, a condenser, a drying filter, a throttle valve and an evaporator.

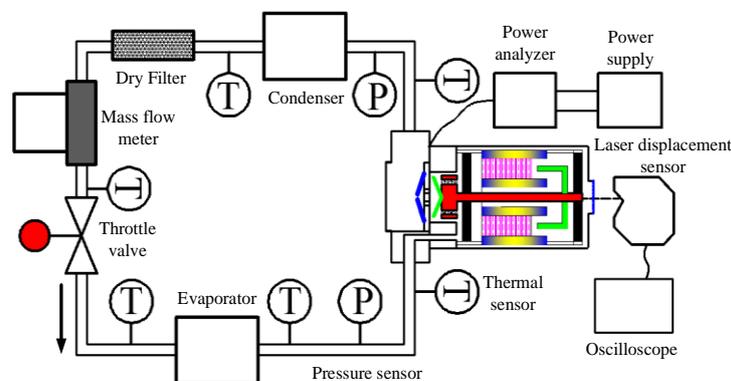


Figure 3. Test system chart of linear compressor

Figure 4. shows the power supply and online monitoring system of the linear compressor. The power supply system consists of a signal generator, a NF power supply and a power analyzer. The working process is that the signal generator generates a sinusoidal voltage signal, which is amplified by the NF power supply, and the electrical parameters of the amplified electrical signal are measured by a power analyzer.

The online monitoring system consists of a voltage sensor, a current sensor, a laser displacement sensor and a high-frequency dynamic pressure sensor. It can monitor the compressor's excitation signal (voltage) and response signal (piston displacement, current, the gas pressure) at the same time. A voltage sensor and a current sensor are installed between the power analyzer and the linear compressor in order to monitor the voltage and current signals input to the linear compressor; a set of laser displacement sensor is installed to obtain piston displacement online; A high-frequency dynamic pressure sensor is installed on the cylinder to monitor the gas pressure signal in compression chamber online, the installation position is shown in Figure 5.

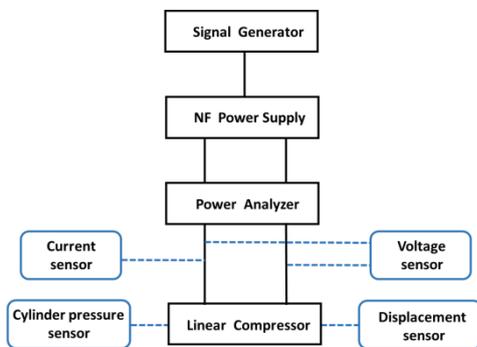


Figure 4. The power supply and online monitoring system

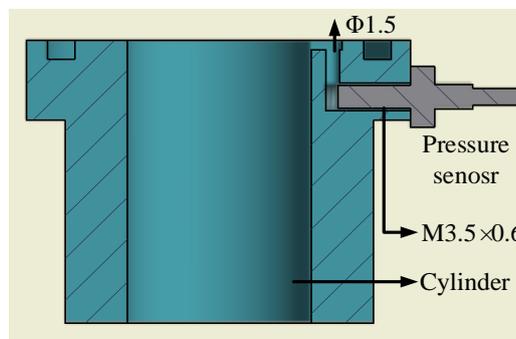


Figure 5. The installation position of the pressure sensor

3.2 Test conditions

Table 1 provides the test conditions of linear compressor. The work fluid is R134a.

Table 1 Test conditions

Items	Value(Unit)	Items	Value(Unit)
Evaporation temperature	5 (°C)	Refrigerant charge	110(g)
Condensation temperature	35(°C)	Stroke	8(mm)
Superheating temperature	5 (°C)	Operating frequency	50-70(Hz)
Supercooling temperature	5 (°C)	Ambient temperature	25(°C)

4. Results and Discussion

4.1 Experimental study on response characteristics

The linear compressor is driven with a sine voltage. The gas pressure, current, and piston displacement response curves can be obtained online at the same time.

Figure 6. shows the displacement response curves at different frequencies. It can be seen that the waveform of the displacement response curve at different frequencies is similar to sine. Figure 7. shows the current response curves of the compressor at different frequencies. It can be seen that the current response curves at different frequencies have non-linear distortions that deviate from the

sinusoidal curve. The current distortion is particularly serious and two wave crests appear within one cycle at 60 Hz.

Figure 8. shows the gas pressure curve in different frequencies under the same working conditions, the four working stages (compression(a-b), exhaust (b-c), expansion(c-d) and suction(d-a1)) of the linear compressor can be clearly distinguished. The slope of the compression and expansion process increases with frequency. During the exhaust process, the cylinder pressure will bulge and then decrease. This is due to the sudden opening of the exhaust valve resulting in a sudden pressure change in the compression chamber. During the suction process, the suction valve fluctuates slightly. It is obvious that the gas pressure is non-linear.

Figure 9. shows the piston displacement response curve, current response curve and standard sine curve at 60Hz. The current curve and the displacement curve in Figure9. are divided into four processes according to the time points in Figure 8. In the compression process (a-b), the measured displacement curve does not coincide with the standard sine curve, and the displacement curve is higher than the sine curve. At this time, the current curve is seriously distorted. During the exhaust process (b-c), the nonlinear distortion of the measured displacement curve is small, and the current curve has no nonlinear distortion. During the expansion process (c-d) and suction process (d-a1), the measured displacement curve and current curve also have no nonlinear distortion.

To quantitatively illustrate the difference of the displacement and current curve compared with the standard sine curve, the Total Harmonics Distortion (THD) is introduced (Tang 2014) ^[8], and the expression of THD is:

$$THD_u = \frac{D_H}{D_1} = \frac{\sqrt{\sum_{h=2}^{\infty} (D_h)^2}}{D_1} \quad (4)$$

Where D_1 is root mean square (RMS) value of the fundamental wave, D_H is root mean square value of the high order harmonic component.

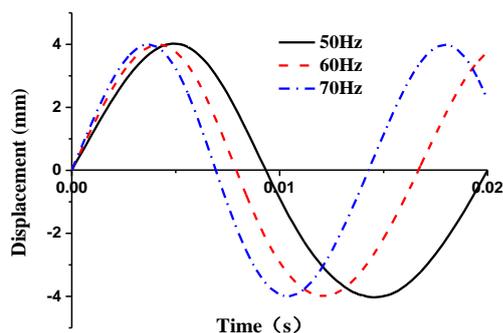


Figure6. The displacement curve in different frequencies

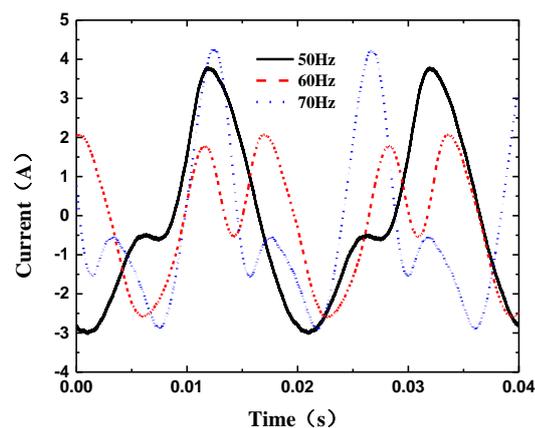


Figure7. The current curve in different frequencies

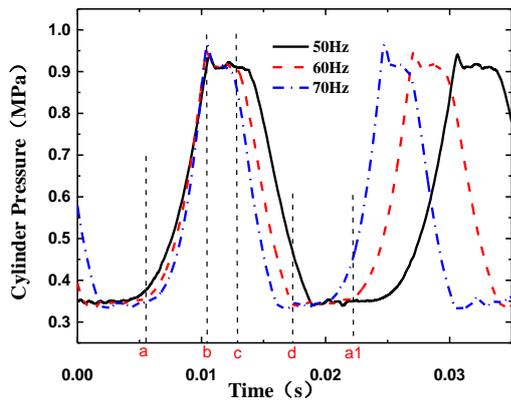


Figure 8. The gas pressure curve in different frequencies

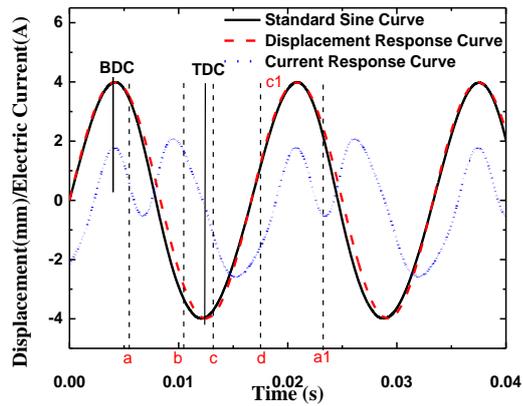


Figure 9. The displacement and current synchronous curve at 60Hz

Figure 10. shows the THDs of the displacement and current curves at different frequencies. It can be seen that the distortion rate of the displacement is small, and the distortion rate decreases with increasing frequency. In general, the THD of the displacement is within 7%, but the current has relatively large distortion at different frequencies, and the distortion rate is as high as 73.7% at 60Hz.

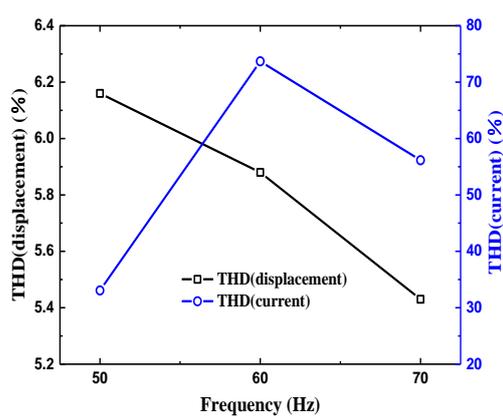


Figure 10. The THD of the displacement and current curves at different frequencies.

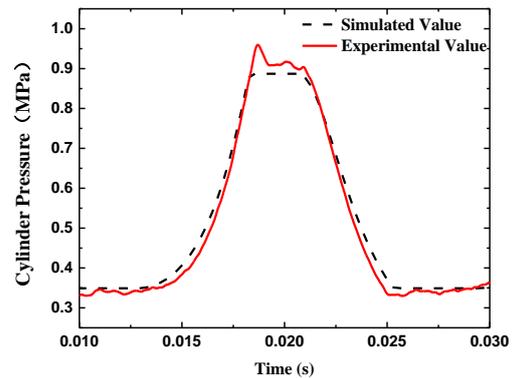


Figure 11. The comparison between the calculation and measurement curve of gas pressure

4.2 Numerical Simulation Based on Nonlinear Dynamic Model

The nonlinear characteristics of the linear motor are ignored in the model. The parameters such as motor constant, equivalent resistance and equivalent inductance are treated as constants, and the damping coefficient in the mechanical system is treated as constant. Therefore, there only is non-linear gas loading in the model. This model takes 60Hz as an example to analyze the cause of current distortion. Figure 11. shows the comparison between the calculated gas pressure and the actual measured gas pressure. Since the suction and exhaust valve is treated as an ideal valve, the difference between the two during the suction and exhaust process is large. Figure 13. shows the calculated displacement curve, measured displacement curve and standard sine curve. It can be seen that both the calculated and measured displacement curves deviate from the standard sine curve at the ellipse

marked in the Figure12. Figure 13. shows the comparison between the calculated and measured current curves, it can be seen that the calculated current curve also shows a significant double-peak distortion. This phenomenon shows that the cause of the large distortion of current is mainly the non-linear characteristics of the gas load, rather than the non-linear characteristics of the linear motor.

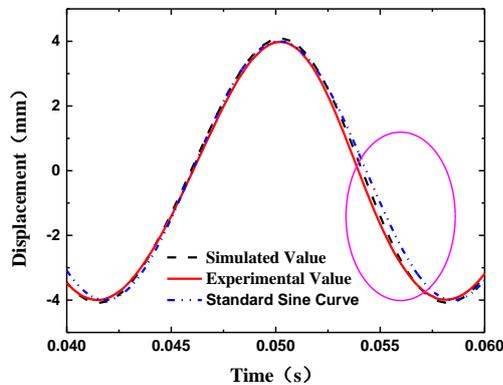


Figure12. The comparison between calculation and measurement curve of displacement

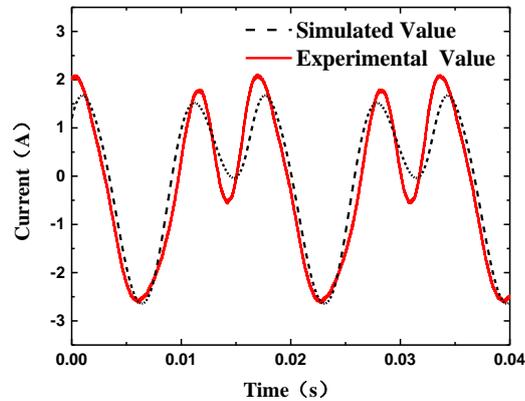


Figure13. The comparison between calculation and measurement curve of current

5. Conclusion

In this paper, the nonlinear response characteristics (the gas pressure, displacement and current response) of an oil-free moving coil linear compressor driven by sinusoidal at different frequencies are experimentally studied and theoretically analyzed based on the nonlinear dynamic model. The following conclusions can be drawn from this research:

- 1) The response characteristics of moving coil linear compressors (piston displacement curve, current curve and the gas pressure curve) have been experimentally measured simultaneously. The results show that the gas pressure curve, displacement curve and current curve are nonlinear (non-sinusoidal) when the moving coil linear compressor is driven by sinusoidal voltage. Among them, the current waveform has relatively large deviation from sinusoid.
- 2) By introducing the Total Harmonics Distortion (THD), the nonlinear distortion of waveforms is quantitatively evaluated. When the driving frequency is 60Hz, the THD of current has a maximum value of 73.7%, and the current has two peaks in one cycle. The THD of piston displacement has a maximum value of 6.2% at 50Hz.
- 3) In a working cycle, the nonlinear distortion of displacement and current occurs only in the compression process, and the displacement waveform and current waveform have almost no distortion in other processes.
- 4) The severe distortion of the current curve is mainly caused by the non-linearity of the gas pressure.

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