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Piston position sensing and control in a linear compressor using a search coil

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ABSTRACT

Linear compressors with clearance seals are well established for cryocoolers using either a Stirling cycle or pulse tube. However, both piston stroke and piston offset require detection and control in valved compressors. In order to manufacture linear compressor in large scale, then a simple, robust, and cheap control system is required with a minimum of sensors and actuators. This work introduces an approach to sensing the position of the piston using a search coil. The piston stroke is detected by calculating the peak-to-peak flux linkage in relation to the measured drive voltage and current. The piston offset is proportional to an integrated modulus of the back electromotive force (emf) of the search coil. Two PID (proportional-integral-derivative) controllers were developed to control the piston stroke by adjusting the drive voltage and a solenoid valve and bleed flow to control the piston offset. Experimental results validate the proposed compressor control technique.

Détection et régulation de la position du piston dans un compresseur linéaire en utilisant un serpentin de recherche

Mots clés : Compresseur linéaire ; Système de régulation ; Serpentin de recherche ; Course de piston ; Segmentation de piston

1. Introduction

A linear compressor is an attractive proposition for electronics cooling applications because it offers several benefits compared to traditional compressor technologies, as pointed out by Bailey et al. (2011). A linear compressor does not have a crank mechanism to drive the piston, but is driven directly by a linear motor. Oil-free operation is possible, and this is a significant advantage with respect to the heat transfer performance of the condenser and the evaporator in a refrigeration system as it would allow the use of compact heat exchangers. The absence of oil widens both the choice of refrigerants and their operating temperature range. Eliminating the need for the oil return reduces constraints on pipe sizing and will lead to a reduction in pressure drop losses. In a high efficiency linear machine, the piston operates resonantly in order to minimise the drive current and

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Nomenclature

A	area [mm^2]
C	constant
COP	coefficient of performance
f	frequency [Hz]
I	current [A]
k	factor of displacement or spring rate [N/mm]
LVDT	linear variable differential transformer
M	mutual inductance [H]
P	pressure [bar] or power [W]
PID	proportional-integral-derivative
PWM	pulse-width-modulation
R	resistance [Ω]
RMS	root mean square
S	stroke [mm]
V	voltage [V]
x	displacement [mm]

Subscripts

Φ	flux linkage [Weber]

Subscripts

0	initial
1	cylinder
a	amplitude
b	body
dis	discharge
emf	electromotive force
g	gas
int	integration
m	mean or main or mechanical
s	search oil
suc	suction

ohmic losses. Resonance is determined by the moving mass and stiffness, which has at least two components, the mechanical springs and the gas spring. Bradshaw et al. (2011) concluded that the potential for this technology to be scaled to small physical sizes is better than for conventional compressors.

Sunpower have been developing linear technologies for a long period. LG has licensed Sunpower's linear technology and has been marketing linear compressor systems for household refrigeration since 2002. A more recent development by Embraco is an oil-free linear compressor designed for R134a and R600a. Embraco launched their oil-free linear compressor in 2014 with a license from Fisher & Paykel. Bradshaw (2012) has also built a linear compressor model that was validated by testing a prototype linear compressor that used a moving magnet motor.

In a linear compressor, the flow rate is controlled by amplitude modulation, which means that there is no need for stop–start operation in which temperature gradients have to be re-established (Tassou et al. 1983). The linear compressor is a free piston system, so that the cooling capacity can be modulated by the piston stroke control. The stroke is controlled by adjusting the drive voltage (excitation voltage). Huang and Chen (2002) found that the stroke of the piston in a linear compressor varies markedly with the outlet pressure variation. A slight increase in outlet pressure will cause a dramatic decrease in stroke. Huang and Chen studied the system dynamics of a linear compressor and designed a controller to regulate both the stroke and frequency of the compressor during operation using a displacement transducer. Kim and Jeong (2013) and Kim et al. (2011) proposed an inherent capacity modulation technique for the LG linear compressor by developing a numerical model of the compressor system. The capacity modulation is based on the clearance volume, which is the distance from the top position of the piston to the cylinder head.

Fig. 1 shows the schematic of a free-piston linear compressor system. Apart from stroke control, the linear compressor requires control of the piston offset. The problem of piston offset (or drift) in a linear compressor is caused by the differential pressure generated across a radial clearance seal, which has a fluctuating pressure on one side of it (piston-cylinder) and an almost constant pressure on the other (body). The pressure differential is given by

$$\Delta P = P_{1,m} + P_{1,a}\sin(\omega t) - P_b \quad (1)$$

where P_b is the pressure in the motor body and $P_{1,m}$ is the mean pressure in the cylinder.

If the body pressure, P_b, is equal to the mean working pressure, $P_{1,m}$, then the net volumetric flow taken round one cycle is zero. The mass flow rate, however, is proportional to the mean density, and this is higher when the piston is closer to cylinder head than when it is closer to compressor body side. Thus there will be a net mass flow from the working side to the body volume across the clearance seal, which will decrease the mean working pressure and increase the body pressure. Eventually an equilibrium point will be reached when this effect is counterbalanced by the pressure differential in the opposite direction.

If there is a difference between the mean working pressure $P_{1,m}$ and the body pressure P_b, there will be a net axial force, which is only counteracted by the mechanical springs,

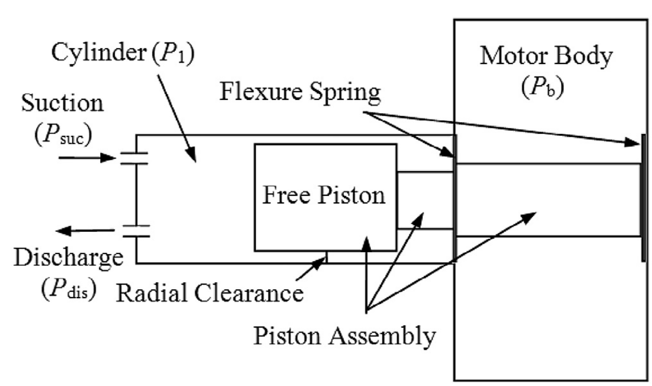

Fig. 1 – Schematic of the linear compressor system.