Proceedings of IMECE2008
2008 ASME International Mechanical Engineering Congress and Exposition
October 31-November 6, 2008, Boston, Massachusetts, USA

IMECE2008-67290

ANALYSIS OF THE IDLING START OF THE MOVING COIL LINEAR COMPRESSOR

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ABSTRACT

The linear compressor is driven by a linear motor. Because it has no crankcase, the piston motion and its control of the linear compressor are differing from that of the conventional reciprocating compressor. For a moving coil linear compressor, mechanical and electromagnetism system are modeled. The open loop and closed loop transfer functions of the system in no-load condition are obtained derived from these equations. The Matlab software is applied to analyze the stability, time domain and frequency domain of the system. Simulation results show that the linear compressor is stable, but the overshoot is relative high, which must be adjusted. This conclusion will be benefit for the design of the idling start of the moving coil linear compressor.

NOMENCLATURE

M	the mass of the moving coil and piston,[kg]
X	piston displacement, [m]
t	time,[s]
C	viscous damping coefficient, [N.s/m]
K	spring constant，[KN/m]
B	magnetic flux density,[T]
U	electric voltage, [V]
I	current strength, [A]
l	the length of coil, [m]
L	coil inductance, [H]
Δp	the pressure difference, [Pa]
A	the cross-section area of the piston, [m^2]
$G(s)$	the open loop transfer function
s	complex frequency
$H(s)$	feedback element, its value is 1
$\Phi(s)$	the closed loop transfer function
B_0	high-order term coefficient ratio
z_j	zero of the closed loop

p_i	real pole of the system
ξ	damping ratio
ω_n	undamped oscillation frequency

1. INTRODUCTION

In contrast to a conventional reciprocating compressor, a linear compressor is a positive displacement, piston-type compressor in which the piston is driven directly by a linear motor [1]. Linear motors are simple devices in which axial forces are generated by current in a magnetic field. Because all the driving forces in a linear compressor act along the line of motion, there is no sideways thrust on the piston, substantially reducing bearing loads and allowing the use of gas bearings or low viscosity oil.

In a linear compressor, the piston motion is not defined by the geometry of the driver mechanism as in a conventional reciprocating compressor. Both the amplitude and mid position of the piston motion can change and these are dictated by the mechanical, electromagnetic and pressure force acting on the piston. The linear compressor is now proven in a variety of hardware. Its efficiency, modulation, oil-free option, and features that should make it compete successfully with conventional compressors over wide range of applications [2].

The changeability if the piston stroke is one of the characters of the linear compressor. It can make the compressor easy start at differential pressure and adjust to the change of the load. The change of the piston stroke can lead to the change of the pressure ratio, clearance and dead point of the compressor. Huang, B. J.[3], Tae, W.C.[4], LEE H K[5], Choe GS[6] and Tae-Won Chun[7] research on the strategy of control for a linear compressor. But the idling start of linear compressor is comprehensive difficult problem. This paper takes the moving coil linear compressor for example, by founding motion equations to analysis stability, time and frequency of control system.

2. MOTION ANALYSIS OF THE MOVING COIL LINEAR COMPRESSOR

A schematic moving coil linear compressor is showed in Fig. 1. It uses permanent-magnet to excite. When alternate current flows though the coil, at the function of magnetic field, the coil generates alternate axial force which makes the piston do reciprocating motion to compress the gas. This compressor has many characteristics such as simple construction, compact, high efficiency, lower starting current flow and so on.

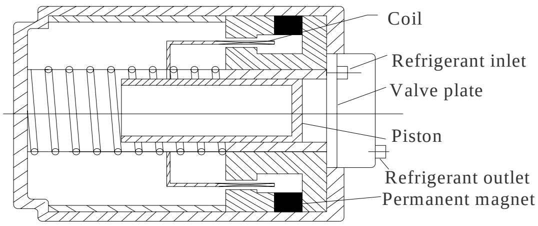

Fig. 1 The construction of moving coil linear compressor

As showed in Fig. 1, the function of the mechanical system is

$$M\frac{d^2X}{dt^2}+C\frac{dX}{dt}+KX=BIL-\Delta p \qquad (1)$$

The function of electromagnetism system is

$$U=L\frac{dI}{dt}+BI\frac{dX}{dt}+RI \qquad (2)$$

According to documentation 4, choose M=0.3 kg, C=7 N.s/m, K=7.365KN/m, B=0.25 T, l=42m, L=0.0165 H, R=4Ω.

In equation (1) ΔP is the change of the gas which belongs to disturb variable. Because we only do research on the no-load characteristic of the system, take no account of it. This system is combined with electromagnetism system and mechanical system, in which electric voltage U is input variable, and displacement X is output variable. Applying the Laplace transform, the open loop transfer function is obtained:

$$G(s)=\frac{X(s)}{U(s)}=\frac{Bl}{MLs^3+(MR+CL)s^2+(CR+B^2l^2+Lk)s+RK} \qquad (3)$$

All the properties of a system is depended on the closed loop function, and the closed loop function can be obtained from the function underside

$$\Phi(s)=\frac{G(s)H(s)}{1+G(s)H(s)} \qquad (4)$$

The closed loop function can be expressed as follow:

$$\Phi(s)=\frac{B_0\prod_{j=1}^{m}(s-z_j)}{\prod_{i=1}^{q}(s+p_i)\prod_{k}^{r}(s^2+2\xi\omega s+\omega^2)} \qquad (5)$$

3. ANALYSIS OF THE NO-LOAD MOVING CHARACTERISTIC

3.1 Time analysis

3.1.1 Stability analysis

Pole determines the inherence moving attribute of the system. Its position determines the stability and rapidity of moving modality. When the pole has negative real part or is a negative real number, the corresponding modality must be convergent. Through computing from function (4), this system has a real pole p_1=-171.09 and a pair of conjugate complex (pole) of which the real part is negative $s_{1,2}$= -36.83±182.84i. Because that the pole of the closed loop are negative and in the left part of plane s, and the transient state component of time response will reach zero with the time increase, we can estimate this system is steady.

3.1.2 time domain response

Fig. 2 is step response of the system, and this is a third-order system. The pole y=0.000469s, delay time t_d=0.0109s, rise time t_r=0.0201s, pole time t_p=0.0244s, adjusting time t_s=30.1s, overshoot M_p%=31.37%.The characteristics of this system are: (1) t_d, t_r, t_p, t_s response the quick starting speed; (2) overshoot is related to damping ratio, and Mp illuminates that damping ratio is moderate.

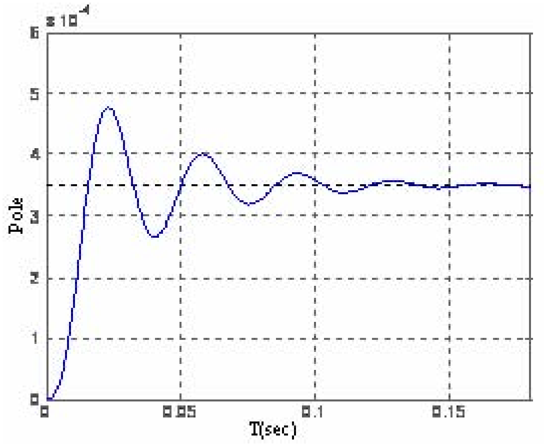

Fig. 2 Step response of the system

3.2 Root locus analysis

Fig. 3 is the root locus diagram, and this system has no zero. The root locus starting from the two symmetrical poles start from the left part of s plan, and intersect the virtual axis into the right part of s plane. The root locus will not meet with growing of closed loop gain kg. Another root locus of the system starting from the pole on the negative real axis in the left part of s plane, reaches infinite distance. This figure illuminates that when closed loop gain k_g=2.12×10^3, the double conjugate roots of the system are on the root locus; when kg is bigger than 2.71×10^3, the system is unstable.

3.3 Frequency analysis

Frequency characteristic is the frequency related to the input and output complex sign ratio at steady state when the linear system or segment effected by sine function. It attributes the dynamic law of system.

Fig. 4 is Bode diagram of system (the upper figure is magnitude, the nether figure is phase). Its harmonic frequency ωr=156.7rad/s, and damping ratio ξ=0.197. The expression of magnitude is

$$L(\omega) = 20\lg \frac{1}{\sqrt{(1-\frac{\omega^2}{\omega_n^2})^2 + 4\xi\frac{\omega^2}{\omega_n^2}}} \tag{6}$$

when ω<<ω_n, L(ω)≈-64.1dB;

when ω>>ω_n,   L(ω)≈-40lgω/ωn.

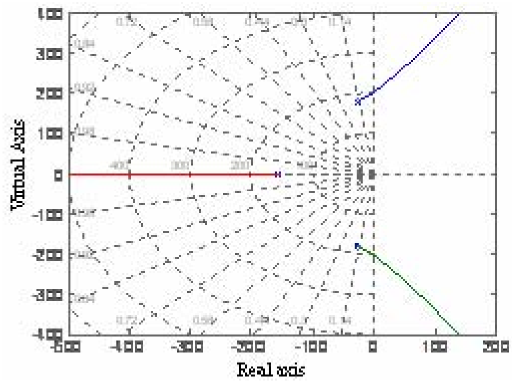

Fig. 3 Root locus diagram of the system

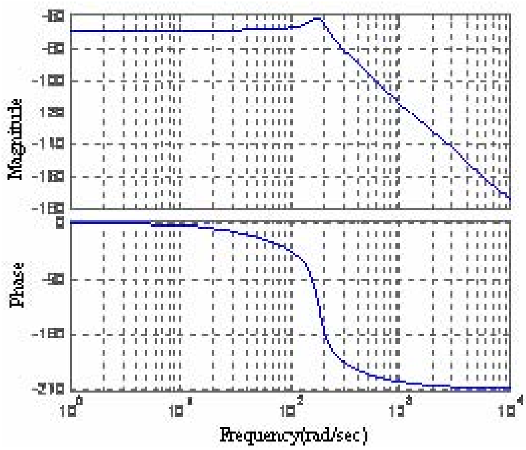

Fig. 4 Bode diagram of the system

We can see from Bode diagram, the frequency of this oscillation segment is ω_r. The magnitude characteristic reaches the max at harmonic frequency, and the pole depends on damping ratio. If the harmonic frequency of system is over, it can cause the overshoot of dynamic response over. It can influence stability of system.

The expression of phase is

$$\varphi(\omega) = -\arctan\frac{2\xi\frac{\omega}{\omega_n}}{1-\frac{\omega^2}{\omega_n^2}} \tag{7}$$

when ω=0, φ(0)=0°;

when ω=ω_n,.φ(ω_n)=-138°;

when ω→∞, φ(ω_n)=-180°.

Damping ratio can influence the change rate of φ(ω) at the neighborhood of ω=ω_n. The smaller the damping ratio, the bigger the change rate.

Fig. 5 is Nyquist diagram. Because that the number of pole of transfer function G(s) at s plane is zero, and Nyquist diagram does not enclose point (-1,j0). According to Nyquist criterion, the number of pole of closed loop system at the right of s plane is zero. So the closed loop system is steady.

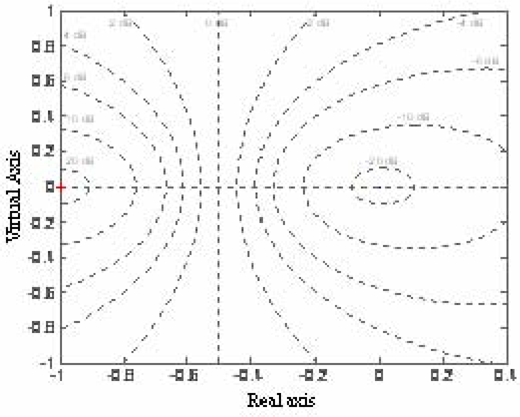

Fig. 5 Nyquist diagram of the system

4. CONCLUSIONS

According to the characteristic of the moving coil linear compressor, system motion equations are built. When using Matlab software to analyze the stability, time domain and frequency domain of the system, we get:

(1) The moving coil linear compressor is almost stable at no-load stage according to the stability analyses and Nyquist diagram;

(2) According to time-domain analysis, root locus diagram and Bode diagram, the overshoot of the moving coil linear compressor at idling start is relative high, and the damping ratio should be increase to lower the overshoot.

The list conclusions will be helpful for the design of idling start of the moving coil linear compressor.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China under the project 306004.

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