Resonance Optimization in Linear Compressor

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Abstract

Resonance is a condition under which the system resonates or vibrates at natural frequency i.e. Operating or exciting frequency matches the natural frequency of the moving mass. Resonance in the vibration industry is considered to be harmful for the long life of the equipment since the amplitude of the vibration under resonance is very high, it causes damage to the structure due to increased stress levels. But there are some resonant equipments like Linear compressor which perform with maximum efficiency under resonance condition. The present paper presents results generated by the mathematical simulation of linear compressor to achieve resonance. Under resonance the amplitude of the piston is highest with minimum input power requirement (Maximum efficiency condition). A linear compressor consists of an oscillating motor and a piston rigidly coupled to it. Oscillations of the linear motor are directly transferred to the piston. Piston performs compression and suction alternately similar to the reciprocating compressor. Since the crank and the connecting rod mechanism are absent in the linear compressor the friction losses are minimum and mechanical efficiency of linear compressor is maximum. Linear compressor is one of the highest available efficiency compression technology.

Keywords—Resonance, natural frequency, Linear compressor, optimization.

1. Introduction

Linear compressor: Linear compressor is a gas compressor where the piston moves along a linear track. The linear compressor is driven by a linear motor directly coupled with a piston and springs for resonant operation. In a linear compressor, a resonant spring is used to obtain a piston stroke with small thrust of a linear motor. Since there is no conversion of rotary to linear motion, all the forces of the linear compressor act along a single axis i.e. the axis of piston motion. This operation along a single axis and direct coupling between the motor and piston generates minimal side loads that prevents contact between the piston and cylinder and hence reduces wear and tear of piston. This characteristic of very low side load & vibrations makes this machine very silent in operation (Generates less than half of the dB noise as compared to reciprocating compressor).

Advantages of linear compressor:

- Silent operation
- No mechanical linkages (crank, connecting rod)
- Minimum friction loss.
- Easy part load operation & modulation to reduce energy bills.

Mathematical model [1]:

The development of model starts with a free body diagram of piston as shown in figure below. Forces acting on the piston are due to combined springs, including the gas effects and the electrodynamics driving force. Mass of the piston includes a portion of the spring mass and the driving coil mass.

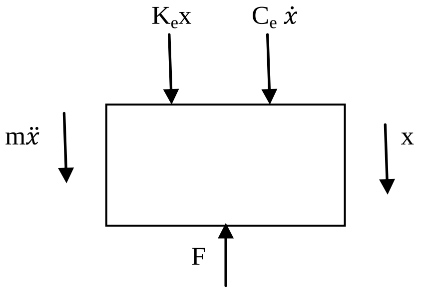


Fig 1: Free Body Diagram

Let K_e be the equivalent spring constant, C_e be the viscous damping constant and M_e be the resonating mass of the system. The equation of motion that governs mechanical part of the system is, therefore, given by:

$$M_e \frac{d2x}{dt2} + C_e \frac{dx}{dt} + K_e x = F \qquad ..1$$

Where, $K_e = K_P + Kg$

K_P = Mechanical spring stiffness

K_g = Gas spring stiffness

And

Motor Force, $F = B_e\, l_e\, I$ ..2

where

B_e is the effective magnetic flux in (web/m^2) that acts on coil winding.

l_e is the effective length of coil wire in (m).

I is current in (Amp) passing through the circuit.

The circuit equation is:

$$B_e\, l_e \frac{dx}{dt} + R_e\, I + L_e \frac{di}{dt} = V \qquad ...3$$

Where,

L_e is the inductance of coil, Henry.

Re is the resistance of the coil, Ohm.

2. Resonance

Resonance is the tendency of a system to oscillate with greater amplitude at some frequencies than at others. Frequency at which the response amplitude is a relative maximum are known as the system's resonant frequencies.

$$fn = \frac{1}{2PI}\sqrt{\frac{Kgas + Kmech}{me}}$$

Where,

fn = Natural frequency of the moving object, Hz.
Kgas = Gas spring stiffness, N/m
Kmech=Mechanical Spring Stiffness, N/m
me = Moving mass of the piston, kg.

2.1 Parameters affecting resonance:

From the above equation for the natural frequency, to achieve resonance the piston should oscillate at this frequency. The electrical supply frequency also should match the natural frequency. Hence linear compressor operation requires a variable frequency power supply.

1. **Moving mass (me):** This includes mass of the piston, mass of the spring, mass of the magnet or coil (Depending on moving coil or moving magnet) and any other mass resonating along with the piston.
2. **Gas spring stiffness (Kgas)**: The gas pressure inside the cylinder during the compression exerts force on the piston surface. If the gas force is dominant, this force would try to push the piston towards the bounce Bottom Dead Center (BDC).
3. **Mechanical Spring Stiffness (Kmech)**: The mechanical spring tries to pull the piston back to the mean position. The driving force (Motor force) should over come all the opposing forces in order to achieve resonance.
4. **Operating frequency**: The exciting frequency should match the operating frequency in order to achieve the resonance.
5. **Motor Force:** Motor force should match all the opposing forces i.e. Spring force, gas force, damping force.

2.2 Input parameters for analysis:

The mathematical model was analyzed for data reported by LG [2] to validate the model. Following is the data considered for analysis,
Refrigerant: R410A
Piston Diameter: 22.5 mm
Piston stroke: 35 mm
Operating Frequency = 60 Hz (For US Market).
Mass varied between = 1.5 to 2.0 kg (Step size: 0.5 kg)
Input Voltage (To be optimized to ensure optimized driving force for achieving full stroke condition).
For resonance Ke = me*omega^2

Mechanical spring stiffness was varied from 0.8 to 0.9 of the resonance condition (Remaining is assumed to be gas spring).

Operating frequency = 55 Hz to 65 Hz (Step size: 5 Hz)

3. Mathematical simulation results:

Following sections provide with the parametric analysis for resonance optimization for linear compressor.

3.1 Effect of Mass on resonance:

3.1.1 Results for Moving mass of 1.5 kg

a. Piston stroke(mm) and Velocity(m/s) Vs time(sec)

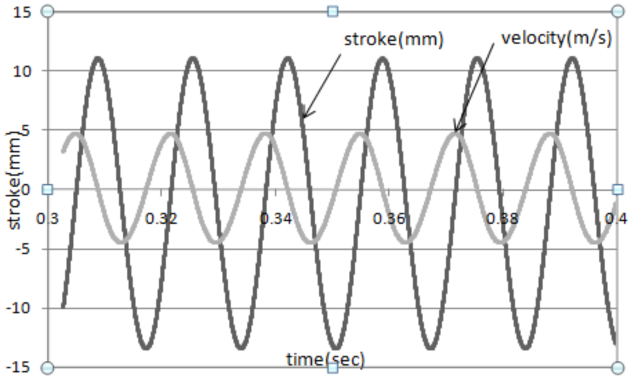


Fig 2. Piston stroke (mm) and Velocity (m/s) Vs time (sec)

Ideally the piston should operate between +17.5/-17.5 mm stroke. When mass of the piston is 1.5 Kg, we get minimum stroke. To get the maximum stroke, we may increase the input voltage. Here in this case, gas forces are dominant compared to inertia force and pushing the piston more to bounce space.

b. Compressor P-V diagram:

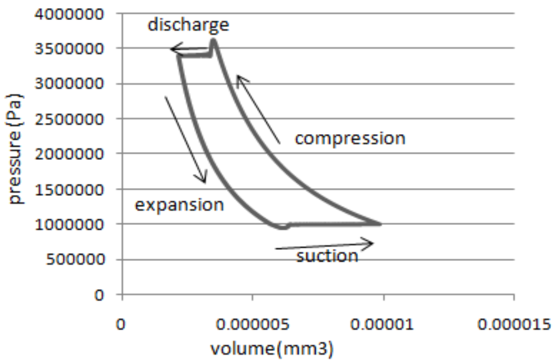


Fig.3 Compressor P-V diagram

c. Valve displacement (mm) Vs time (sec)

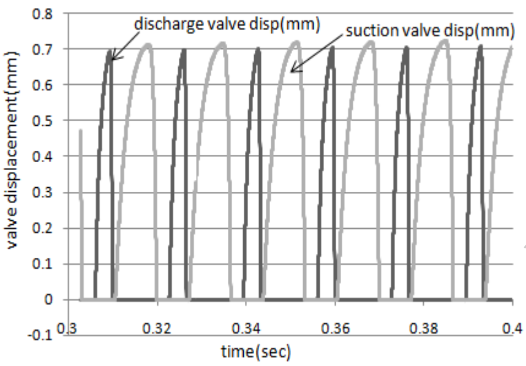


Fig.4 Valve displacement (mm) Vs time (sec)

d. Temperature (K) Vs Time (sec)

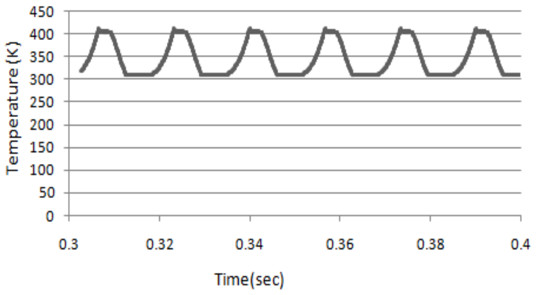


Fig.5 Temperature (K) Vs Time (sec)

e. Pressure (Pa) Vs time (sec)

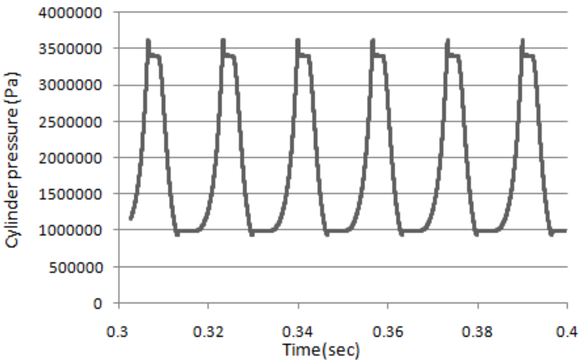


Fig.6 Pressure (Pa) Vs time (sec)

3.1.2 Results for moving mass of 2.0 kg

a. Piston stroke(mm) and velocity(m/s) Vs time(sec)

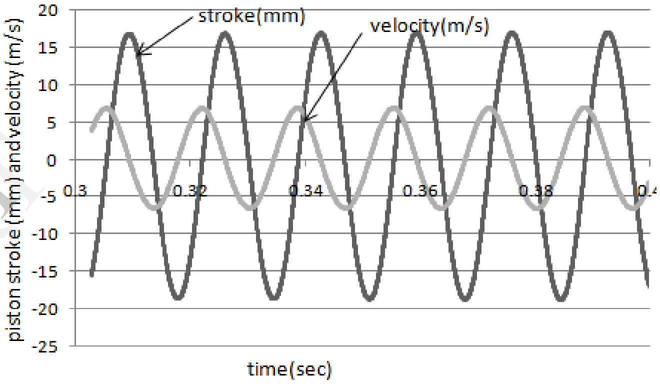


Fig.7 Piston stroke(mm) and velocity(m/s) Vs time(sec)

In this case, we get 35mm total stroke, which is a good operating condition. For achieving the resonance condition, the piston should operate between +17.5/-17.5 mm stroke. Hence a mass of 2 Kg was selected for further analysis.

b. P-V diagram

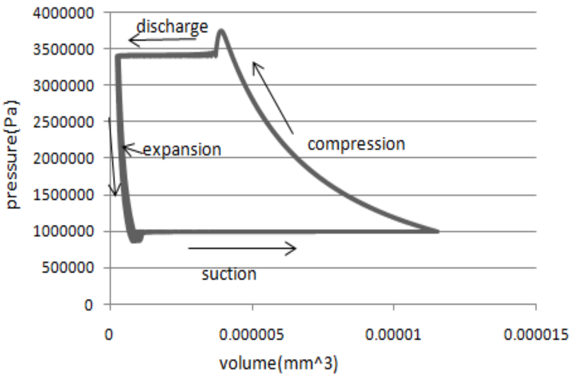


Fig.8 P-V diagram

c. Valve displacement(mm) Vs time(sec)

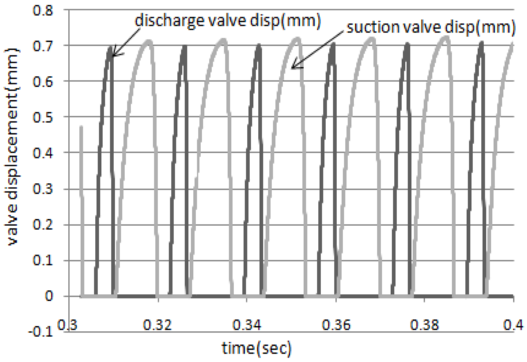
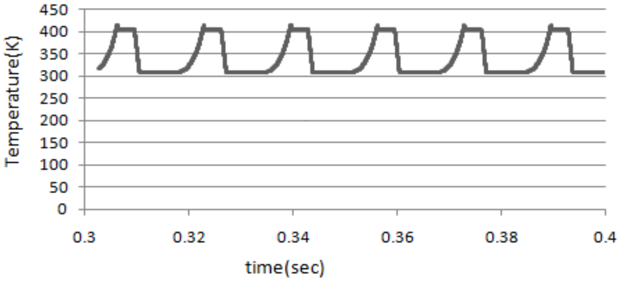
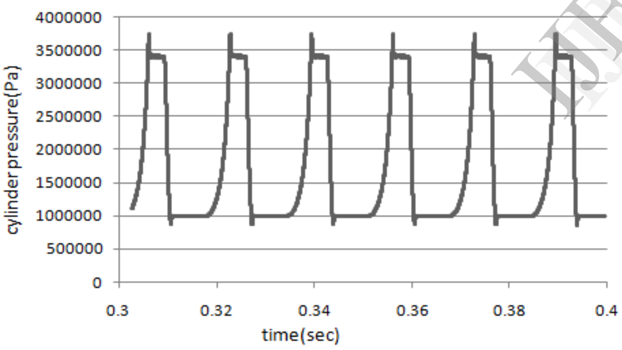


Fig 9. Valve displacement(mm) Vs time(sec)

d. Temperature (K) Vs time (sec)

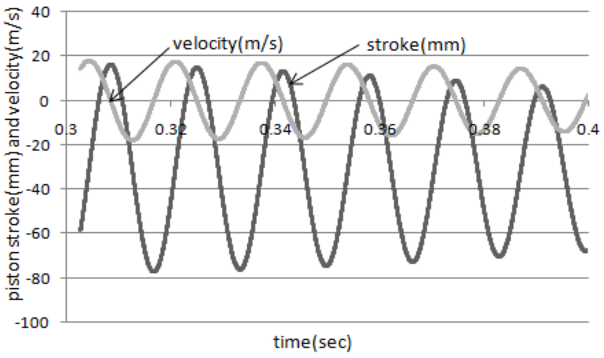


e. Pressure(Pa) Vs time(sec)



3.1.3 Results for moving mass of 2.1 kg

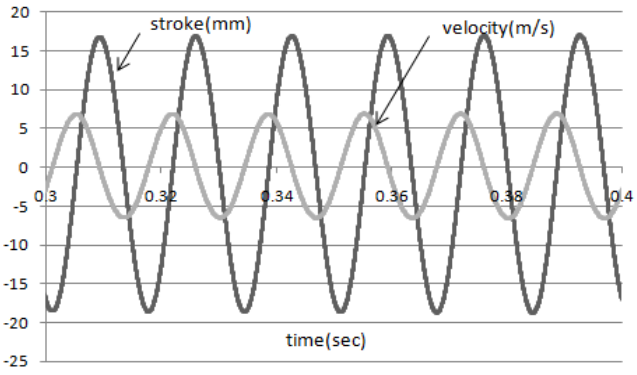
a. Piston stroke(mm) and velocity(m/s) Vs time (sec)



Here in this case, the gas forces are dominant and pushing the piston more to other end. To get the resonance condition, we may increase the input voltage to the positive side.

3.2 Effect of spring stiffness on resonance:

1. Results for spring stiffness K is 0.89



For achieving resonance condition , we need equal stroke in both sides i.e. positive as well as negative side. Here in this case, we get equal stroke in both sides. Therefore this is a good operating condition.

3.3 Effect of operating frequency on resonance:

The resonance condition of a system is very sensitive to driving or electrical supply frequency.

3.4 Effect of input voltage (or driving force) on piston stroke:

a. Piston Stroke(mm) and velocity (m/s) Vs time(sec)

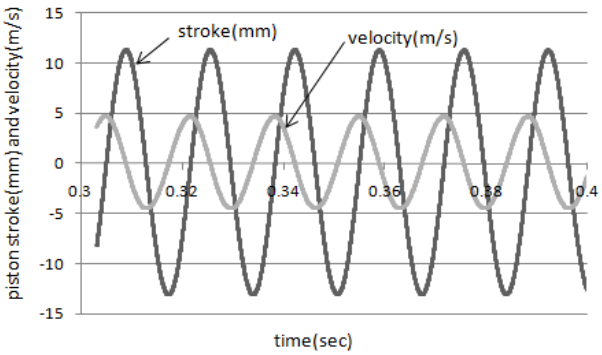
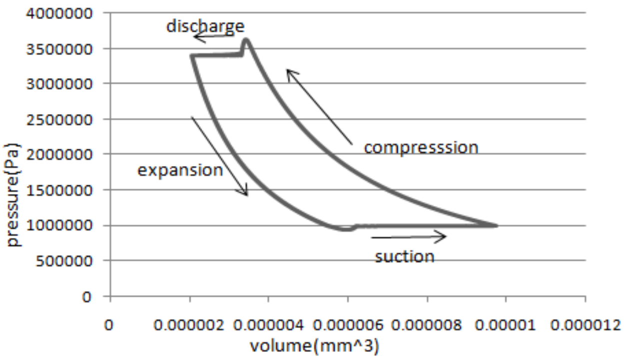


Fig. 10.Piston stroke (mm) and velocity (m/s) Vs time (sec)

b. P-V diagram



c. Temperature(K) Vs time(sec)

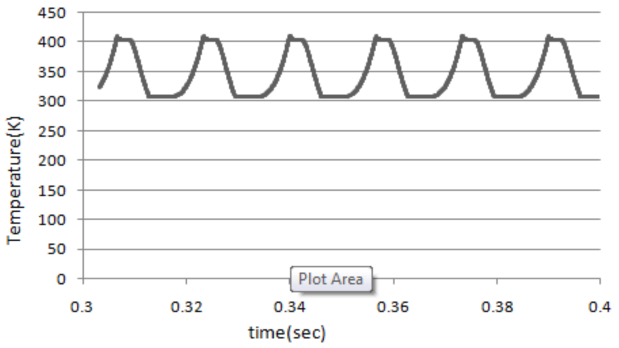
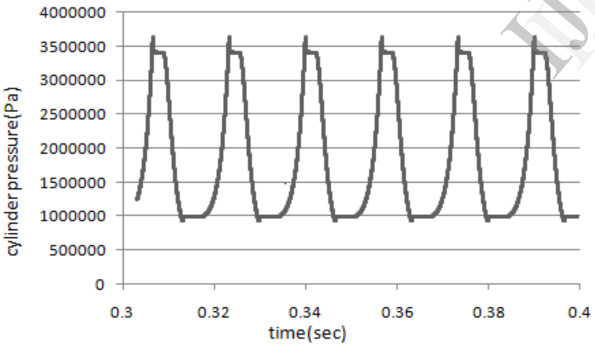


Fig.11 Temperature (K) Vs time (sec)

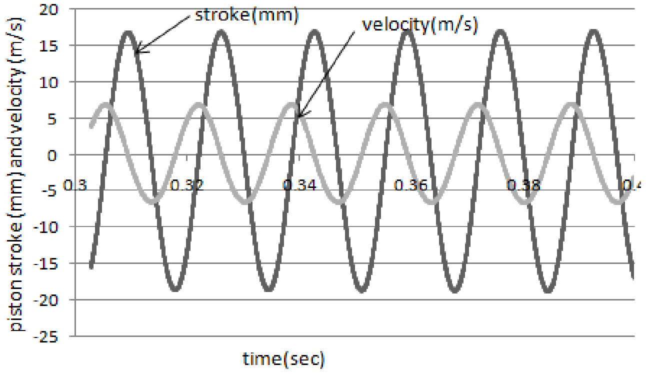
d. Cylinder pressure (Pa) Vs time(sec)



4. Performance of Linear compressor at resonance:

Following graphs are the optimized graphs under resonance condition showing,

1. Piston stroke and velocity Vs Time



2. P-V diagram

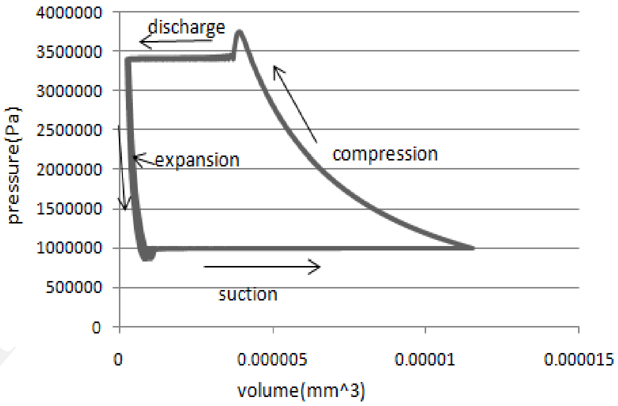
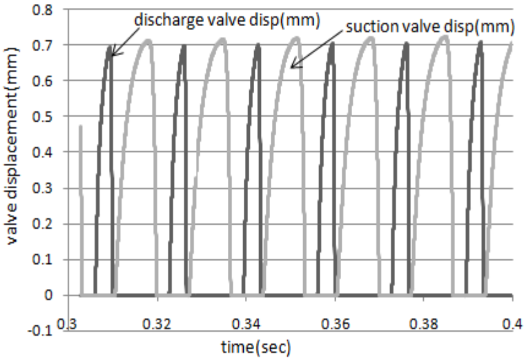
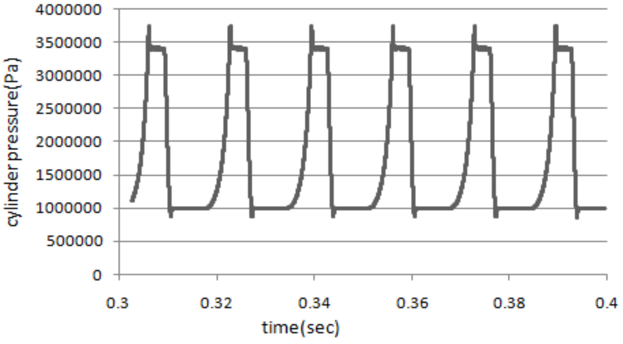


Fig .12 .P-V diagram

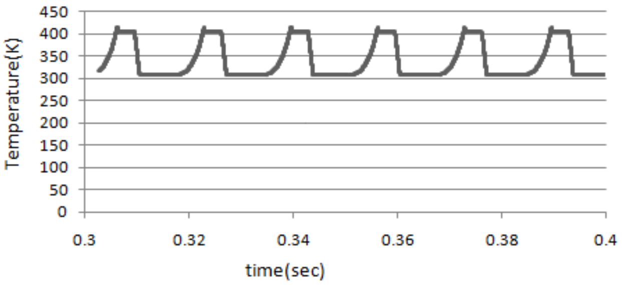
3. Valve displacement Vs Time.



4. Cylinder Pressure Vs Time.



5. Cylinder Temperature Vs Time.



5. Observations

For achieving the resonance condition, we need equal piston stroke on either side of mean position i.e. equal in positive as well as negative side.

To get equal stroke on either side or to nullify gas spring effect on piston motion it is must to tune the supply frequency to resonant frequency. To get full stroke once resonance is achieved we need to fine tune input supply voltage.

6. Conclusions

1. To get high efficiency in linear compressor, we need to achieve resonance condition (i.e. Maximum stroke and minimum input power).
2. To understand effect of different parameters on performance of linear compressor and to optimize different parameters, we analyzed various parameters with the code developed.
3. The resonance condition of the system is very sensitive to driving or electrical supply frequency. Piston oscillates with the same frequency as electrical supply frequency, for resonance this should match with the natural frequency of the moving mass.

7. References

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[2] Hyuk Lee, Sang-sub Jeong, Chel-woong Lee, Hyeong-kook Lee, **“**Linear Compressor For Air-Conditioner”, L. G. Electronics, Seoul, South Korea, C047, 17th International Compressor Conference, Purdue, USA.