Study on a linear compressor with metal-bellow replacing conventional cylinder-piston unit

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Linear compressor, which acts as a pressure wave generator in regenerative refrigerator system, is an important element converting electric power to acoustic power. And its high efficiency, flexibility and survivability exhibit multifold advantages over conventional compressors. This paper presents the study of a linear compressor of moving-coil type with metal-bellow unit, which is made up of a wavelike thin wall pipe and is used to produce the pressure oscillation. The influence of mechanical parameters and acoustic loads is investigated when it works resonantly. It provides some guidelines for designing an efficient linear compressor with metal-bellow assembly.

INTRODUCTION

The linear compressor, which is developed to meet the increasing demand of high efficiency and high reliability, has advantages over traditional reciprocating compressor on several aspects including high efficiency, simple mechanism and flexible capacity by controlling the stroke, etc. This paper presents the study of a linear compressor with metal-bellow unit instead of cylinder-piston unit for thermoacoustic refrigerator applications, which have a ring-shaped moving coil and a stationary magnet. Due to non-leaking interface between the front and back sides of bellow unit, the working gas is protected from being contaminated by the gas emitted from the coil and lubrication oil inside. Further more, it can avoid the friction, precision mechanical technology. We use linear bearings other than flexure bearings, because of unlimited displacement and availability; however, it may bring a little friction loss. In the computation, it can be found that the linear compressor has a highest efficiency for optimized design. And the influence of moving mass, acoustic load and working frequency of the linear compressor are investigated.

MATHEMATIC MODEL OF LINEAR COMPRESSOR

The linear compressor is an electro-mechanical system, which transforms electrical power to mechanical energy. Consequently, from Kirchhoff law and Newton second law, the following equations can be given:

$$R_{elec} i + L_{elec} \frac{di}{dt} + B_g l v = V \,, \quad B_g l i - \tilde{p} \cdot A - R_{mech} v - K x = M \frac{dv}{dt}$$

where, R_{elec} and L_{elec} are the resistance and the inductance of the coil, B_g is the magnetic flux density of

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the gap, where the coil moves, v is velocity, V is the voltage, K is the suspension spring stiffness, R_{mech} is damping coefficient of mechanical system, M is moving mass.

Using complex notations, $i=\tilde{I}\cdot e^{j\omega t}$, $v=\tilde{v}\cdot e^{j\omega t}$, $V=\tilde{V}\cdot e^{j\omega t}$. Superscript '~' represents the oscillating value. Substitute these variables into the first two equations, and they can be reduced to:

$$\tilde{V}=(R_{elec}+jX_{elec})\tilde{I}+\frac{\tau}{A}\tilde{U}\,,\quad \tilde{P}=\frac{\tau}{A}\tilde{I}-\frac{R_{mech}+jX_{mech}}{A^2}\tilde{U}$$

where $X_{mech}=\omega M-K/\omega$ is the imagery of the mechanical impedance. And the acoustic load is:

$$R_{acoust}+jX_{acoust}=\frac{\tilde{p}}{\tilde{U}}$$

Solving these three equations leads to the following expressions:

$$\tilde{I}=\frac{\tilde{V}(R_{am}+jX_{am})}{(R_{elec}R_{am}-X_{elec}X_{am}+\tau^2)+j(R_{elec}X_{am}+X_{elec}R_{am})}$$

$$\tilde{p}=\frac{\tilde{V}A\tau(R_{acoust}+jX_{acoust})}{(R_{elec}R_{am}-X_{elec}X_{am}+\tau^2)+j(R_{elec}X_{am}+X_{elec}R_{am})}$$

$$\tilde{U}=\frac{\tilde{V}A\tau}{(R_{elec}R_{am}-X_{elec}X_{am}+\tau^2)+j(R_{elec}X_{am}+X_{elec}R_{am})}$$

where $R_{am}=R_{mech}+A^2R_{acoust}$ and, $X_{am}=X_{mech}+A^2X_{acoust}$, which can be discovered that the convert coefficient of acoustic impedance to mechanical impedance is square of the swept cross-section area. From the impedance network [1], this relation is much more clear. The electric power into the compressor and the acoustic power out of the compressor are given as follows:

$$W_{elec}=\frac{1}{2}\mathrm{Re}\left[V\tilde{I}^*\right]=\frac{V}{2}\mathrm{Re}\left[\tilde{I}^*\right],\quad \Delta\dot{E}_2=-\frac{1}{2}\mathrm{Re}\left[\tilde{p}\tilde{U}^*\right]$$

the superscript '*' denotes complex conjunction. The electro-acoustic efficiency is given as follows [2]:

$$\frac{1}{\eta_{trans}}=\frac{\mathrm{W}_{elec}}{\Delta\dot{E}_2}=1+\frac{R_{mech}}{A^2R_{acoust}}+\frac{R_{elec}}{A^2\tau^2R_{acoust}}\left[R_{am}^2+X_{am}^2\right]$$

Obviously, setting $X_{am}=0$ leads to the resonance state of the system. The X_{am} depends strongly on not only mechanical system and acoustic load themselves, but also the acoustic-mechanical convert coefficient of impedance.

METAL-BELLOW ASSEMBLY AND PROTOTYPE OF THE LINEAR COMPRESSOR

Metal-bellow assembly is used to replace the conditional cylinder-piston Unit, so as to avoid high accuracy mechanical fabrication and installation and oil lubrication. The metal-bellow unit can be made up by dozens of dishing metal slice welded together at the edges, or formed by a thin-wall wavelike pipe (see Figure 1). The welding metal-bellow has lower spring stiffness than the molding one, and has more potential ability of deformation. Basically, the smaller the deformation of each wave, the longer longevity the bellow has. Figure 2 is our prototype of the linear compressor. Inside the upmost part is the metal-bellow unit with a 75 mm diameter and 100 mm high.

Figure 1 The welded (left) and molder (right) metal-bellows

Figure 2 Picture of the linear compressor

COMPUTATIONAL RESULTS AND ANALYSIS

In our design, the magnetic flux density of the gap is 1.1T. The copper wire of the coil is about 180 meters long, which has a diameter of about 0.63 mm, and the electrical resistance is 10.6 ohms. And the maximum swept volume is about 60cc. Under these conditions, this paper investigates the influence of the moving-mass, the acoustic load and frequency response of the system.

<u>Moving mass</u>

The moving mass of the linear compressor is about 2 kg, which includes the mass of shaft, the coil and 1/3 mass of the suspension springs and metal-bellow. As it mentioned above, the efficiency is independent of the moving mass when the system is working resonantly, however, it affects the piston stroke and the phase difference between the voltage and the current.

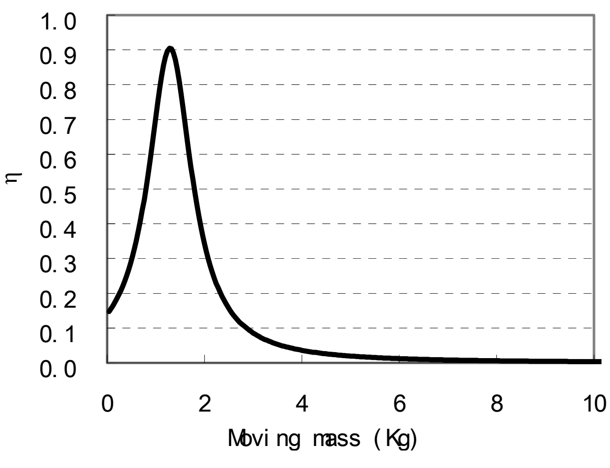

Figure 3 Efficiency varying moving mass

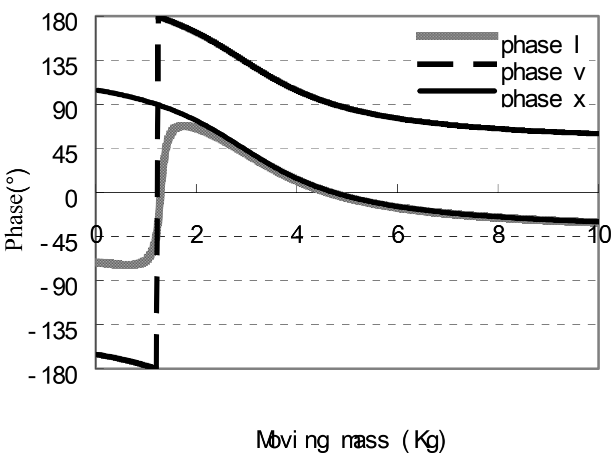

Figure 4 Relative phase of I, v and x vs. mass

Keeping the other variable unchanged, we obtain the relationship between the efficiency and the moving mass (See Figure 3). And in Figure 4, it shows the relationship between the relative phase of current, velocity and stroke versus the moving mass respectively. Obviously, with the increase of the moving mass, the efficient increases quickly and then reduces sharply. It can be said that at the peak efficiency, the compressor reaches the "resonance state". At the same time, the voltage and current are in phase and the phase between the current and stroke is near 90° [3], that is, the magnetic force is lag the stroke by 90° . It can be interpreted that when the system works resonantly, the compressor consumes only a little electric power to overcome the power dissipations in the electrical, mechanical and acoustic resistance.

<u>Frequency response and acoustic load</u>

The linear compressor can be treated as single-degree-of-freedom spring-mass-damped system. And the linear compressor is sensitive to the acoustic load. If the acoustic load and the compressor match each other, the system reaches a highest efficiency (see Figure 5, "A.L" means the acoustic load). However, the relative phase diagram of the current, stroke and velocity is similar to the Figure 4 (see Figure 6). In Figure 5, $\eta_{\_max}$ represents the maximum efficiency for different acoustic load. If the acoustic load smaller than the appropriate load, the efficiency drops sharply. Therefore, it is important to match the compressor to the acoustic load.

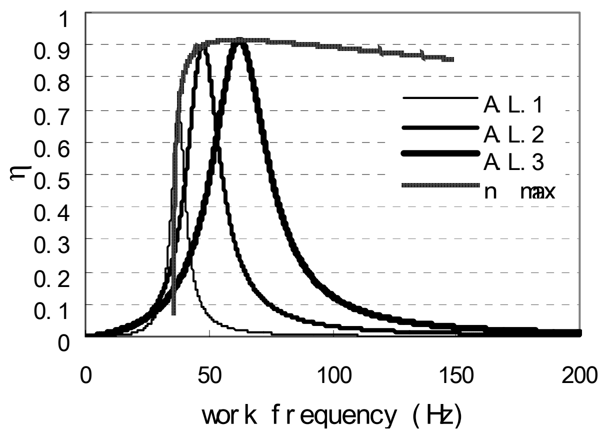

Figure 5 Efficiency Vs. frequency and difference load

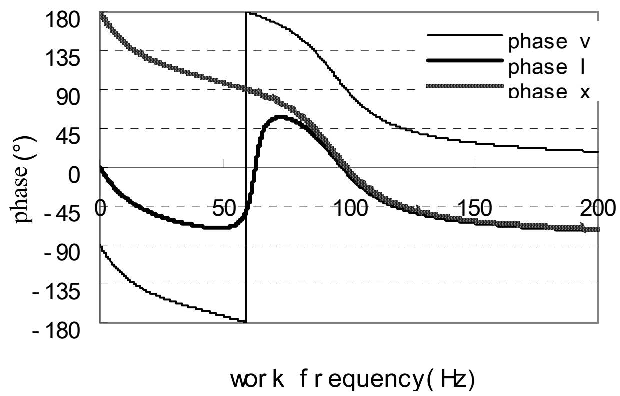

Figure 6 Relative phase diagram of I, v, x

CONCLUSION

Theoretically, it is important for the linear compressor to work resonantly to achieve high efficiency and low electrical power consumption. And it's also important to match the acoustic load to the compressor to obtain high efficiency. Furthermore, the phase between current and stroke must be 90° when it works resonantly.

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