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Research paper

Acoustic power measurement of linear compressors

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ABSTRACT

The linear compressor works as an important driver for high frequency regenerative cryocoolers. The acoustic power output of the compressor is a critical parameter in the design and the optimization of a linear compressor. To measure this parameter, several approaches based on different theories have been developed. In this paper, the RC load approach and the back chamber approach have been applied to a linear compressor to measure the acoustic power output. The results measured by the approaches indicate a good consistency with the theoretical calculation and reveal the connections between different approaches.

The difference between the acoustic power at the piston surface and the exit of a linear compressor has been analyzed based on the experimental results from the RC load approach and the back chamber approach. The volume flow rate difference which accounts for the acoustic power difference is studied theoretically. Furthermore, based on the RC load approach, the optimum impedance together with the impedance cloudy map for the linear compressor to reach its highest efficiency has been obtained by analyzing the experimental and the theoretical results.

1. Introduction

With the development of the space discovery, the cooling method for various detectors in satellites has been explored in depth. High frequency regenerative cryocoolers like Stirling cryocoolers and pulse tube cryocoolers have been widely used to cool down the detectors [1,2]. Since the invention of the Oxford type linear compressor in 1980s, the linear compressor has become the common choice for driving high frequency cryocoolers because of its high efficiency and reliability [3]. The electricity-driven linear compressor provides the acoustic power, which can be further transferred into the cooling power at the cold finger. Since the cooling power of a cryocooler is closely related to the acoustic power at the inlet of the cold finger, the linear compressor becomes an essential component. The efficiency and the reliability of a cryocooler depend on its compressor as well. The development of advanced high frequency cryocoolers always comes into being along with the improvement of linear compressors [4–7]. The acoustic power output of the compressor is a key parameter for the improvement of the linear compressor because it indicates the capacity of the compressor. However, the accurate measurement of this power is hard to achieve due to the difficulty of monitoring the oscillation flow rate.

Several methods have been proposed to measure the acoustic power output of the linear compressor both directly and indirectly. The hot wire anemometer is a common choice for measuring the oscillation flow rate. With additional pressure sensors, the hot wire anemometer can measure the acoustic power output of the linear compressor as well [8]. Although the application of the hot wire anemometer is proved to be effective, the disadvantages of this method are unignorable. In this method, a tiny wire is put in the oscillation flow which influences the flow itself. The frequent change of flow direction forces the wire to deform repeatedly and makes the wire fragile. Also, a rather complicated system is needed to ensure the accuracy. In addition, there are some other indirect methods which do not influence the flow itself such as the back chamber approach and the linear variable differential transformer (LVDT) approach. The back chamber approach relies on a pressure sensor inside the back chamber of the compressor while LVDT approach requires LVDT components on the pistons. Both these two approaches are not applicable to compressors that are without such additional structures. Furthermore, these two approaches focus on the acoustic power at the surface of the piston rather than at the outlet of the compressor. The compression space can result in the difference between acoustic powers at these two positions. Another approach called the resistance-capacitance load (RC load) approach for the

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acoustic power measurement was also applied in practice [9]. This method is based on the thermoacoustic theory and the equivalent principle. Since this method is rather convenient and reliable, it deserves further study and validation.

There have been some experiments comparing the RC load approach and the LVDT approach [10]. In order to further validate the RC load approach, the RC load approach, the theoretical calculation approach and the back chamber approach are compared in this paper. The principles of these three approaches are introduced first, which is followed by the introduction of the experimental measure system. With this measure system, several experiments are carried out on a linear compressor and the results are analyzed to show the consistency and difference between these three approaches.

2. The basic theory of the linear compressor and the measure principles

The theoretical model of the linear compressor is introduced for a better understanding of the acoustic power output and the efficiency of the linear compressor. The principles of the RC load approach and the back chamber approach are introduced as the basis of the experimental measure system.

2.1. The theoretical analysis of the acoustic power output

According to an idealized model of a linear compressor, the electrical power input and the acoustic power output can be calculated together with the theoretical efficiency. This idealized model is based upon the following assumptions:

(1) The capacitance of the linear compressor is ignored.
(2) There is no flow resistance in the compressor.
(3) The pressure and the volume flow oscillations are both considered as harmonic.
(4) The working fluid helium is an ideal gas.

Fig. 1 shows a schematic diagram of a linear compressor. The theoretical analysis of the linear compressor can be found in related literatures [11–14]. The mechanical impedance and the acoustic impedance of the linear compressor are defined as [13]:

$$\boldsymbol{Z_e} = R_e + j\omega L_e = R_e + jX_e \tag{1}$$

$$\boldsymbol{Z_m} = R_m + j\left(\omega M - \frac{k_s}{\omega}\right) = R_m + jX_m \tag{2}$$

$$\boldsymbol{Z_a} = \frac{\boldsymbol{P_c}}{\boldsymbol{U}} = R_a + jX_a \tag{3}$$

with $\boldsymbol{Z_e}$ the electrical impedance, $\boldsymbol{Z_m}$ the mechanical impedance and $\boldsymbol{Z_a}$ the acoustic impedance, R_e the resistance of the compressor, L_e the inductance of the compressor, the angular frequency, M the mass of the piston and k_s the spring stiffness.

According to the voltage balance and force balance discussed in related literatures, the electrical power input of the linear compressor can be calculated as:

$$W_e = \frac{|\varepsilon|^2}{2}\frac{R\alpha^2 + R_e(R^2 + X^2)}{|A^2\boldsymbol{Z_a}\boldsymbol{Z_e} + \alpha^2 + \boldsymbol{Z_e}\boldsymbol{Z_m}|^2} \tag{4}$$

with ε the voltage input of the compressor, α the specific thrust of the motor, A the area of the compressor piston, $R = R_m + A^2R_a$ and $X = X_m + A^2X_a$.

The acoustic power output of the linear compressor can be calculated as:

$$W_{a,cal} = \frac{|\varepsilon|^2}{2}\frac{(\alpha A)^2R_a}{|A^2\boldsymbol{Z_a}\boldsymbol{Z_e} + \alpha^2 + \boldsymbol{Z_e}\boldsymbol{Z_m}|^2} \tag{5}$$

According to Eqs. (4) and (5), the efficiency of the linear compressor is:

$$\eta = \frac{W_a}{W_e} = \frac{(\alpha A)^2R_a}{R\alpha^2 + R_e(R^2 + X^2)} \tag{6}$$

This idealized model provides an approach to calculate the acoustic power output and the efficiency of a linear compressor connected with an acoustic impedance. The results from this approach are verified by comparing with experiments [13]. The optimum working condition and the optimum acoustic impedance can also be obtained by applying this model.

2.2. The back chamber approach

Given that the operation frequency of the linear compressor is commonly higher than 10 Hz, the piston moves so fast that the process in the back chamber is adiabatic. Under the assumption of an ideal working fluid, the relation between the pressure at the back chamber and the volume flow rate at the outlet of the compressor is:

$$\boldsymbol{U} = -\frac{j\omega \boldsymbol{P_b} V_b}{\gamma P_0} \tag{7}$$

with $\boldsymbol{U}$ the volume flow rate at the outlet of the compressor, $\boldsymbol{P_b}$ the pressure in the back chamber, V_b the volume of the back chamber, γ the adiabatic index and P_0 the mean pressure.

According to Eq. (7), the acoustic power output of the compressor is:

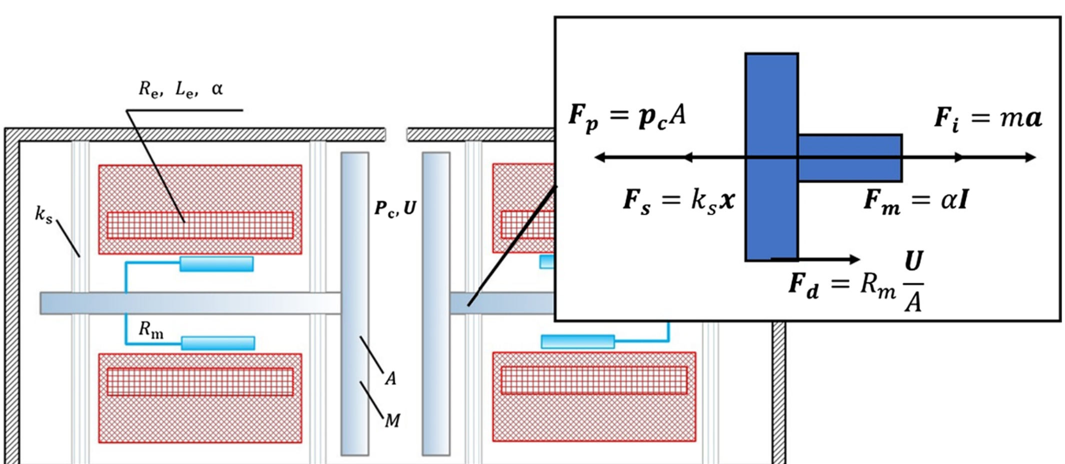

Fig. 1. A schematic diagram of a linear compressor.