Experimental study on a split free-piston stirling cooler for space applications

Zhang Wu, Wu Yinong, Lu Guohua

Shanghai Institute of Technical Physics (SITP), Chinese Academy of Sciences，Shanghai, 200083, P.R,China

With the purpose of lightening Stirling cooler used for space, a split Free-Piston Stirling cooler is designed and assembled based on a previous double-driven split Stirling cooler operated successfully. Compared with double-driven Stirling cooler, the stroke and phase of pneumatically driven displacer in the Free-Piston Stirling cooler are hard to control. In this paper the way of adjusting the stroke and phase, which will give a preferable stroke and phase, is studied experimentally in detail. And some methods of adjusting correlative parameters are achieved. Driven by the same compressor, the cooling performance of the Free-Piston split Stirling cooler under optimal parameters setting is close to that of double-driven Stirling cooler.

INTRODUCTION

Since clearance seal with flexure spring technology was introduced in “Oxford 80K cooler” [1], long life stirling cooler has been used in space widely as one of the important cooling mode. Many companies have participated in the development of this kind of cooler and so does our company. A split Oxford-type Stirling cooler double-driven by linear motors had been developed by SITP and successfully applied in the Shenzhou No.3 space ship mission. It could produce 500mW cooling power at 80K in consuming less than 30w input power. However, the size and the weight of this kind of stirling cooler are more and more difficult to meet some missions with the development of small satellites. It is necessary to make the long-life stirling cooler with smaller size as well as lighter weight.

DESIGN FEATURES AND EXPERIMANTAL APPARATUS

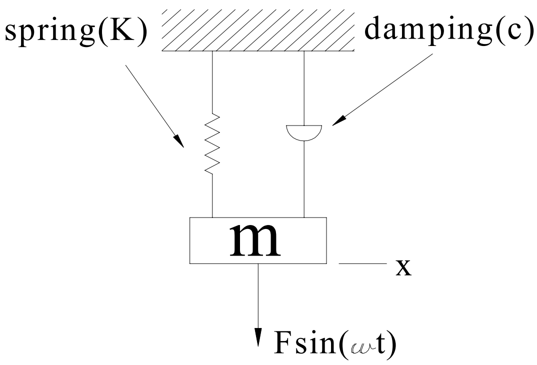

Figure 1 spring-mass-damped system

The displacer in stirling cryocooler can be seen as a single-degree-of-freedom spring-mass-damped system (see Figure 1). The movement of displacer is decided together by the mass of displacer m, the spring constant K and the damping coefficient C.

The natural frequency f_0 of this system is:

$$f_0 = (K/m)^{0.5} / 2\pi \tag{1}$$

And the damping ratio ζ of this system is:

$$\zeta = C/(2\sqrt{K \bullet m}) \tag{2}$$

According to classical analysis of single-degree-of spring-mass-damped system [2], amplitude gain will increase with the decrease of the damping ratio and maximum amplitude gain will occur at a frequency that is somewhat less than the natural frequency in the case of modest degree of damping. The corresponding frequency is referred as resonant frequency and decided by the natural frequency and the damping ratio. It's relatively easy to achieve the natural frequency we prefer through adjusting the spring stiffness, but difficult to get appropriate damping ratio.

In many stirling coolers the seal between piston and cylinder as well as the damping was fulfilled by dry-friction. These coolers are small but at the cost of short lifetimes. Oxford 80K Stirling cooler solved the problem of contact seal by using clearance seal, but in order to produce appropriate damping ratio a linear motor had to be added in the expander. As mentioned above, the motor increases the size and the weight of the Stirling cooler.

In order to meet the long-life requirement and have lighter weight, based on our previous split Oxford-type stirling cooler double-driven by linear motor, an improved free piston expander is designed. Different with previous expander, the motor in it has been abandoned and a new damping modulating structure has been adopted. The schematic of damping modulating structure as well as the measurement system is shown in the Figure 2.

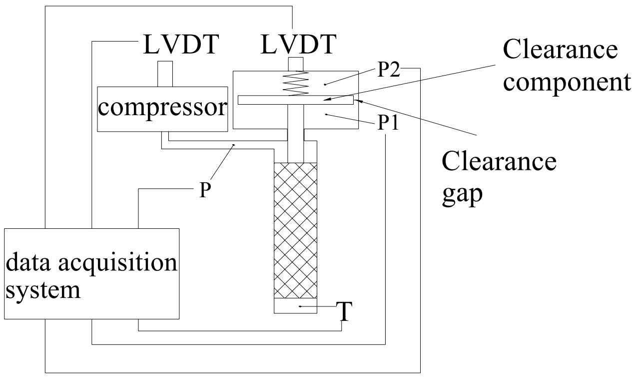

Figure 2 Structure and measurement system

The clearance component divides the pneumatic chamber into two parts. Gas will flow from one chamber into the other chamber through the gap when the clearance component moves reciprocatingly. The gap width being very small, it will hold back the flow of the gas and synchronously the pressure difference between the two chambers will be established. Namely the system has produced a force. So long as the force is in opposite phase with the movement, the force can be seen as a damping force. For better understanding the influence of clearance component on the system, calculation on the movement of displacer is carried out based on the following assumptions:

- For the purpose of simulating the effect of the clearance component on the system, the resistance of the regenerator is neglected;
- Ideal gas and constant properties;
- One-dimensional flow

In order to compare the cooling performance with the previous cooler used in Shenzhou No.3 space ship, the compressor remains the same. Two pressure sensors are placed in the two chambers respectively and a pressure sensor is installed in the pipe to measure the system pressure. Two linear variable differential transformers (LVDT) are used to measure the displacement signal of compressor piston and expander piston respectively. A PT100 is used to measure the temperature of cold finger. Those six signals are all transferred to the data acquisition system, which it's easy to know the phase difference of any two fluctuating signals.

THEORETICAL CALCULATION AND EXPERIMENTAL RESULTS

In order to research the adjusting method on the stroke and phase as well as the optimum matching condition between the compressor and expander, lots of experiments are done based on the various dynamic parameters such as the natural frequency of displacer, the width of clearance gap, charging pressure and the driven frequency. Besides, some theoretical calculation results are utilized to validate some experimental results.

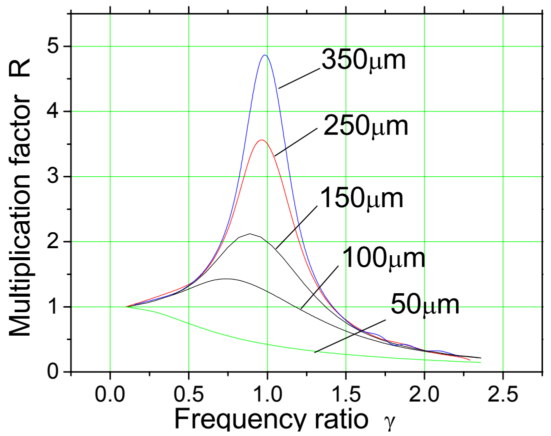

Figure 3 Theoretical calculation on frequency response for different gap width

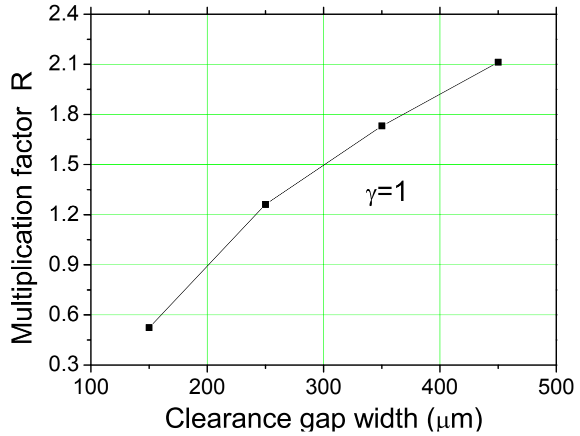

Figure 4 Experimental result on multiplication factor for different gap width

Seen from the curves in Figure 3, similar with the classical frequency response curves in single-degree-of-freedom system, with the increase of the clearance gap width the displacer amplitude gain will increase and the resonant frequency will be closer to the natural frequency. That is smaller the clearance gap width is, bigger the damping ratio is. The experimental results in Figure 4 also illustrate the above conclusion. Because of not considering the resistance of the regenerator the actual multiplication factor is less than that in calculation. In order to avoid too big or too small damping ratio, selecting appropriate width of the clearance gap is very important.

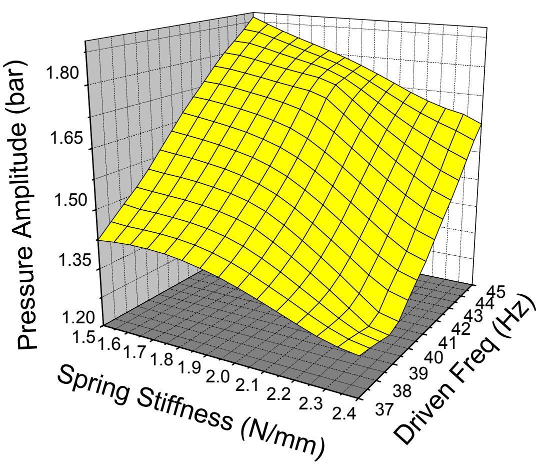

Figure 5 Pressure amplitude curve with different spring stiffness and driven frequency

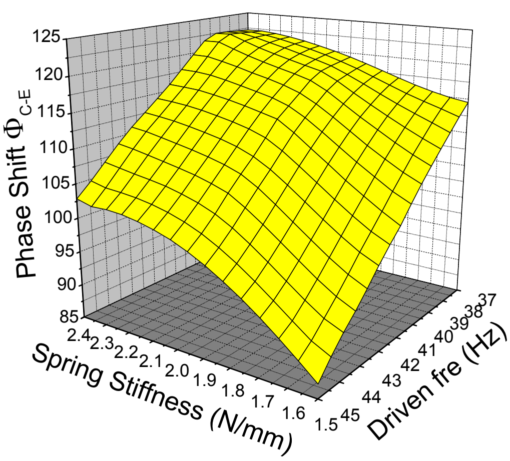

Figure 6 Phase shift curve with different spring stiffness and driven frequency

Seen from the above experimental results in Figure 5 and 6, with the decrease of the driven frequency and the increase of the spring stiffness the phase shift between compressor and expander will increase, while the pipe pressure amplitude will decrease. According to [2] the phase shift between driven force and the displacement of displacer will increase with the rise of the driven frequency. Moreover, the phase of the pressure at low temperature is lag to that at room temperature and the phase shift will increase with the rise of the driven frequency according to [3]. This trend is disadvantageous to our stirling cooler system. The optimum cooling performance will occur when maximum driven force and appropriate phase shift are all satisfied.

The main optimal dynamic parameters of the cooler are as follows: the charging pressure is 15bar, the resonance frequency of the displacer is 46Hz, the breadth of the clearance is 300μm and the operating frequency is 43Hz. The optimal performances of the model cooler are as follows: the lowest cooling temperature is 51K, the maximal cooling power at 80K cooling temperature is 632mw, the input power is 27.3W and the corresponding COP is 2.31%(see Figure 7). The results are close to the level that our previous split Oxford-type double-driven Stirling cooler had reached.

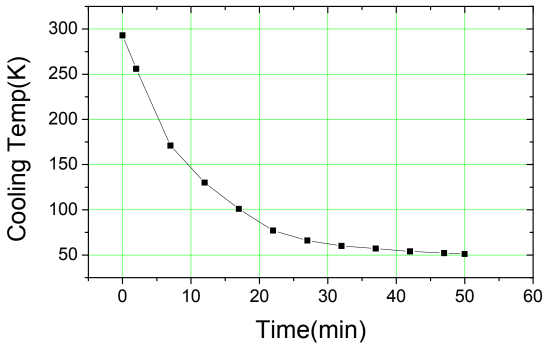

Figure 7 Optimal cool-down curve for our improved cooler

CONCLUSION

An improved expander with clearance component is introduced, which will meet the long life and lighter weight requirement.

The movement of the clearance component can be seen as a kind of damping and it can adjust the stroke and phase of the displacer effectively.

The new expander can obtain 632mW cooling power at 80K in consuming 27.3W input power, which is proved to be a promising method to use in space.

REFERENCES

1. S.T.Werrett, G.D.Peskett, G.Davey, T.W.Bradshaw, J.Delderfield, "Development of A Small Stirling Cycle Cooler for Space-flight Applications," Oxford University, et al, Advances in Cryogenic Engineering (1986) 31 791-799
2. Wenjun Shen, Jinghui Zhang, Mechanical vibration—theory and application, The publishing house of national defense industry, Beijing, (1984) (in Chinese)
3. Kwanwoo Nam, Sangkwon Jeong, Measurement of cryogenic regenerator characteristics under oscillating flow and pulsating pressure, Cryogenic Engineering Laboratory, Korea Advanced Institute of Science and Technology, Taejon, Korea, Cryogenics (2003) 43 575-581