Development of Stirling-type pulse tube cryocooler

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Abstract. Stirling type pulse tube cryocoolers are very attractive for cooling of diverse application because it has several inherent advantages such as no moving part in the cold end, low manufacturing cost and long operation life. A moving magnet type linear motor of dual piston configuration is designed, and this compressor could be operated with the electric power of 100 W at the operating frequency of 50 Hz. A pulse tube cold finger with a double segmented inertance tube was designed for the desired cooling capacity. The coiled inertance tube was assembled inside the reservoir. In experiment, the pulse tube cryocooler is capable of providing the cooling capacity of 2.0 W at 80 K with power consumption of 99.1 W. Random and sinusoidal vibration tests have been conducted to evaluate their performance characteristics and structural integrity.

1. Introduction
Stirling type pulse tube cryocoolers are very attractive for cooling of diverse application because it has several inherent advantages such as no moving part in the cold end, low manufacturing cost and long operation life. The coaxial pulse tube cold finger configuration, which has the similar appearance to the Stirling cryocooler, has been widely used for the cooling of the infrared detectors [1].

A linear compressor is the most critical component of the pulse tube cryocooler. The moving magnet linear motor with the flexure bearing offers various advantages to increasing reliability of the cryocooler and enabling the compact compressor design.

In the pulse tube cryocooler, the phase shifting mechanism performs the function of maintaining the appropriate phase relationships between the pressure wave and the flow. Proper phase relationship must exist in regenerator to operate optimally. An inertance tube with a gas reservoir is effectively used in high frequency pulse tube cryocooler [2].

A single inertance tube with constant inner diameter often has great difficulty in obtaining the desired phase relationship. Therefore, the double-segmented inertance tube with different diameters and lengths, respectively, has been used to achieve a satisfactory phase shift within the acceptable tube length [3].

The optimal match between the pulse tube cold finger and the linear compressor plays a vital role in optimizing the compressor efficiency and in improving cooling performance.

To develop the Stirling-type pulse tube cryocooler, we need to design a linear compressor to drive the pulse tube cryocooler. A moving magnet type linear motor of dual-opposed configuration is designed and fabricated, and this compressor could be operated with the electric power of 100 W and the frequency up to 60 Hz. A single stage coaxial type pulse tube cold finger aiming at over 1.5 W at 80 K is built and tested with the linear compressor.
2. Design of the pulse tube cryocooler

The pulse tube cryocooler is addressed as the split arrangement because the pulse tube cold finger is connected the linear compressor with a connecting tube as shown in Figure 1.

The linear compressor has dual-opposed pistons for dynamic balancing, linear motors, flexure bearings and non-contacting clearance seals. To achieve long lifetime with the linear compressor, it is essential to avoid the contact between the cylinder and the piston. It is well known that the most efficient way to achieve this is by introducing flexure bearings which fully support the piston mass at the front and rear side with high radial stiffness [4]. The linear motor adopts the moving magnet technology to avoid flying leads, contamination of working gas from coil and a non-metallic seal. The pulse tube cold finger adopts the coaxial configuration. The inertance tube consists of two sections with different inner diameter and length. The coiled inertance tube is assembled inside the reservoir to get ease of use of the pulse tube cryocooler.

![Figure 1. Schematic diagram of the pulse tube cryocooler.](image)

| Table 1. Design specification of the pulse tube cryocooler. |
|-------------------------------------------------------------|
| Parameter                  | Values       | Unit  |
| Operating temperature     | 80           | K     |
| Operating frequency       | 50           | Hz    |
| Diameter and length of compressor | 80 / 180 | mm    |
| Max. swept vol. of compressor | 5.6        | cc    |
| Thrust constant of motor  | 10.0         | N/A   |
| Diameter of cold finger   | 19           | mm    |
| Length of pulse tube      | 182          | mm    |
| Regenerator               | #400 stainless steel screens |
| Porosity of regenerator   | 0.653        |       |
| Reservoir volume          | 150          | cc    |

3. Performance of the pulse tube cryocooler

The pulse tube cryocooler have been tested for its cooldown and cooling capacity with heat rejected by chilled water at 293 K. Figure 2 shows the cooldown characteristics of the pulse tube cryocooler with the constant input voltage. The operating frequency and charging pressure are 50 Hz and 2.5 MPa. During cooldown, the power consumption is gradually increased. The pulse tube cryocooler get down to 80 K within 10 minutes. The no load temperature is 59 K with the power consumption of 100 W.
In pulse tube cryocooler, there is a large temperature gradient inside the pulse tube. So there exists the convective heat loss due to the gravitational force. It is well known that the best performance of the pulse tube cryocooler is achieved in the vertical position with the cold end downward. Figure 3 and 4 shows thermal performance of the pulse tube cryocooler at the horizontal and vertical orientation to test sensitivity to gravity.

Figure 3 shows the cooling capacity at 80 K with the variation of the power consumption. Results show a cooling capacity of 2.0 W with the power consumption of 99 W and Carnot efficiency of 5.75 %. The efficiency of the cryocooler somewhat lower than the commercial pulse tube cryocoolers [5,6]. The cooling capacity increases from 0 W to 2.0 W with the power consumption changing from 25 W to 100 W in the vertical direction. When the power consumption of the cryocooler is higher than 55 W, there is little difference in cooling capacity between the horizontal and vertical direction. When the cryocooler is operated with the no-load condition at the cold end temperature of 80 K, the large difference in the power consumption occurs depending with the direction.

Figure 4 shows the cold end temperature with the variation of the power consumption. The cold end temperature decreases with increasing power consumption. So, the temperature difference between the hot end and cold end of the pulse tube increases. With same power consumption, the pulse tube cryocooler in the vertical direction can get the lower cold end temperature. The temperature variation due to the change of the installation direction is very large with a small power consumption. The temperature difference between the horizontal and vertical direction decreases with increasing power consumption.
The natural convection is determined by a buoyancy force caused by the temperature difference between the hot and the cold end. The power consumption or the pressure wave amplitude determines the forced convection. With small input power, the ratio of natural convection to force convection is larger, and the influence of natural convection is more evident. With high input power, the influence of natural convection is weakened [4]. As a result, the gravity effect decreases as the power consumption increases.

The vibration induced by the unbalanced movement of the linear motor are greatly undesired since they cause performance degradations of the IR detector. In order to minimize the induced vibration, the dual-opposed linear compressor configuration was adopted. During the assembly and fabrication process, the balancing of the two sides was checked to minimize the vibration. Figure 5 shows vibrations of the pulse tube cryocooler. Vibration output measurement were conducted using PCB 3-axis accelerometer. In the figure, Z axis denotes the compressor longitudinal axis. The graph shows the acceleration in the 500 Hz range. As shown in figure, the maximum output force occurs at the fundamental frequency of 50 Hz followed by decreasing level at higher harmonics. The maximum output force is below 1 Nrms.

The pulse tube cryocooler has been qualified in random and sinusoidal vibration requirements. Random and sinusoidal vibration tests performed along the three orthogonal axes as shown in Figure 11. Figure 5 and 6 shows vibration levels for the pulse tube cryocooler. In figures, red lines and green lines show the abort and tolerance limits for the test, respectively. Black lines stand for vibration levels of the test. Before and after tests, cooling test of the cryocooler were performed. The cooldown time to 80K of the cryocooler without coolant were 22.6 and 23.3 minutes respectively. The pulse tube cryocooler passed the vibration test by showing unchanged performance and structural integrity.
4. Summary
In this study, we developed a single stage pulse tube cryocooler, which consist of the moving magnet type linear compressor and the coaxial type pulse tube cold finger, for the cooling of the infrared detector. A moving magnet type linear motor of dual-opposed configuration is designed and fabricated, and this compressor could be operated with the electric power of 100 W and the frequency of 50 Hz. The pulse tube cryocooler is capable of providing 2.0 W of cooling capacity at 80 K with 100 W power consumption. Random and sinusoidal vibration tests have been conducted to evaluate their performance characteristics and structural integrity.

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