Development of 5W Class Pulse Tube Cryocooler for Space Use

Y Hiratsuka[1], K Otsuka[2], K Kanao[2] and K Narasaki[2]

[1]Technology Research Center, Sumitomo Heavy Industries, Ltd., Yokosuka, Japan
[2]Industrial Equipment Division, Sumitomo Heavy Industries, Ltd., Niihama, Japan

ABSTRACT

Sumitomo Heavy Industries, Ltd. (SHI) has been developing single-stage Stirling cryocoolers (STC) to cool the infrared sensors and radiation shield for the Earth observation satellite Shikisai and the scientific satellites Suzaku, Kaguya and Akatsuki. In addition, the Superconducting Sub-millimeter-Wave Limb-Emission Sounder (SMILES) and the Hitomi X-ray science satellites are equipped with 4K coolers consisting of a two-stage STC and a JT cooler to realize a liquid helium-free cooling system. Cryocoolers for space use are required to have high reliability, small size, light weight, high efficiency and low vibration. An SHI STC has an active balancer for the expander to reduce the induced vibration from the reciprocation of the displacer and the balancer driver. It is disadvantageous compared to a pulse tube cryocooler (PTC). The performance of a single-stage STC made by SHI has a cooling capacity of 2.2 W at 77 K with an electric input of 50 W. However, users of cryocoolers plan to increase the number of sensors to improve the observation accuracy in the near future; thus a 4K cryocooler with an improved cooling capacity is required. We have been developing single-stage PTCs with a cooling capacity of 5 W at 77 K since 2017. Three types of expanders: in-line, U-shape and co-axial types, were built and tested. The design of the cryocooler and the test results are described in this paper. Also, the induced vibration measurement of the compressor and the performance calculation results by numerical simulation are reported.

INTRODUCTION

Recently, various companies have participated in the space industry, and the development of low-cost and small artificial satellites has become more critical in scientific applications and defense. Sumitomo Heavy Industries, Ltd. (SHI) has a long history of developing cryocoolers and cryostats for satellites. Space cryocoolers are required not only to be highly efficient, but also to be compact and lightweight, to have low vibration and to realize high reliability for maintaining cooling performance even in severe environments. Figure 1 shows a schematic configuration of an SHI single-stage STC equipped with a sensor. In an STC, the expander has a moving part, and the cylinder has a very thin wall to reduce heat conduction loss. The moving parts may not move if the cold head is heavily loaded. For this reason, in order to reduce the weight load on the cryocooler of the cooling stage and the influence on the sensor from the vibration of the cryocooler, a cooling stage supported by a support column from the ambient temperature side is provided separately without connecting the sensor directly to the cold head. The sensor is conductively cooled by thin copper foils. Therefore, the cooling load becomes large due to the heat intrusion from the support

Cryocoolers 22, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

column and the thermal resistance of each parts, and the Dewar vessel also becomes large because the cooling stage is separately installed. This single-stage STC has a cooling capacity of 2 W at 77 K with an electric input power of 50 W. For a PTC expander, the sensor can be installed directly on the cold head, and vibration reduction of the expander can be realized without a controller, which is needed for an STC expander. The compressor motor for an STC is a voice coil type motor (VCM) with no detent force, and a dipole motor is used as a countermeasure against eddy current in the yoke. However, since a VCM has a coil in the gap between the yokes, the energy density is lower than that of a moving magnet motor. If the thrust is increased, the volume of the compressor will increase because the size of the magnet and coil needs to be increased. It is essential to improve the compressor motor efficiency in order to increase the cooling capacity without significant changes to the weight and size of the cryocooler due to the limited space and power supply in a satellite.

In order to increase the cooling capacity and further reduce the size of the system, we developed a 5W PTC, including improvement of the compressor. The design and the test results are reported in this paper.

COMPRESSOR DESIGN AND PERFORMANCE EVALUATION RESULTS

Detailed design of new compressor

Prior to the development of the PTC, a compressor was designed and developed using an STC expander. However, the impedance of an STC expander is slightly different from that of a PTC. So the impedance of the compressor needed to be adjusted. It is calculated that the required cooling capacity for cooling a sensor is over 5 W at 77 K, and the pressure-volume (P-V) work of the compressor that accompanies it is required to be over 70 W. As a result, the design target values of the new compressor were set to have a rated electric input power of under 100 W, a motor diameter of under 90 mm, almost the same weight as the current compressor (under 4 kg) and a compressor efficiency of over 75% (motor efficiency over 85%). Table 1 shows the design target specification values for the maximum electrical input power of the compressor and the motor size.

For the linear motor of the compressor, a moving magnet type with high-energy density was selected, and a moving cylinder type was adopted to position the center of gravity of the moving parts in the center of the motor as much as possible. The bearing of the cylinder uses a newly-developed cantilever-type flexure bearing with high radial rigidity to improve the reliability. A transient magnetic field analysis of the motor was performed to obtain the required compressor P-V work. As a result, the motor efficiency was 88%, and the design target value was obtained (Table 2).

Since the temperature of the compressor section directly affects the amount of outgas released, it is necessary to lower the temperature as much as possible. Since it is necessary to confirm that the Joule heat generation, iron loss, and compression heat of the motor is properly removed during the operation of the cryocooler, a steady-state thermal analysis was performed. The coil winding part is a composite material of copper wire and coating. Since the gap is filled with helium gas, simple solid thermal conductivity cannot be used. Therefore, to determine the thermal conductivity of the composite material, a single cell thermal conductivity analysis was performed by the homogenization method. Figure 2 and 3 show the analysis model of the coil part and the

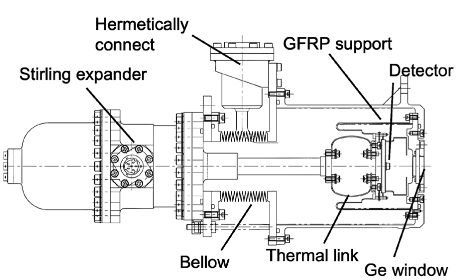


Figure 1. Schematic drawing of Sensor cooling configuration.

Table 1. The design target of this cryocooler.

Item	Value
Operating frequency fco	52 Hz
Cooling power Qch	> 5 W at 77 K
Electrical input power Qinp	< 100 W
Compressor efficiency Effco (Motor efficiency Effmot)	75% (>85%)
Linear motor diameter Dmot	< φ90 mm
Compressor weight Meco	< 4.0 Kg

Table 2. Analysis results of linear motor.

one coil	Item	Value
Input data	Operating Frequency fco	52 Hz
	Coil resistance Rco	4.01 Ω
	Voltage Eco	55.0 Vrms
	Piston displacement Xco	9.44 mm
	Eco and Xco phase difference αco	104 deg.
Output data	Current Ico	1.0 Arms
	Average force Fco	39.67 N
	Coil inductance Lco	66.86 mH
	Input electric power Qinp	47.21 W
	Joule loss I2Rco	3.39 W
	Magnet eddy current EDco	0.94 W
	Yoke eddy current EYco	1.09 W
	F-X FXco	41.45 W
	Motor efficiency Effmot	0.88

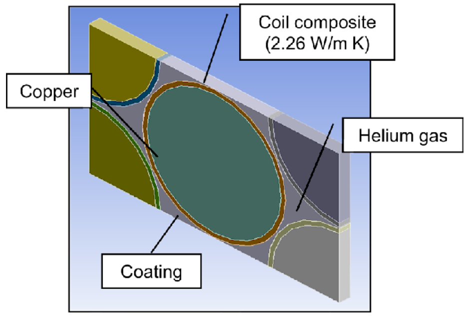
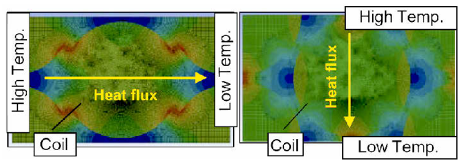


Figure 2. Thermal conductivity analysis model of coil composite material by homogenization method.



a) Radial b) Axial

Figure 3. Heat flux of coil section.

heat flux calculation results. As a result, the thermal conductivity of the coil composite material is 2.24 W / (m • K) in the radial direction and 2.29 W / (m • K) in the axial direction. There is no significant difference between the radial and axial conductivities. The average thermal conductivity was used to study the heat dissipation of the compressor. The analysis conditions are set to be 3.39 W for the coil, 0.94 W for the magnet, and 1.09 W for the yoke. These values are obtained by analysis of the magnetic field and heat conduction at a maximum electrical input power of 100 W, and a compressor heat sink temperature of 30 °C. Figure 4 shows a comparison between the analysis and the coil temperature measurement results using a winding resistance tester. In this figure, it shows that the measured coil temperature is 36.6 °C, while the calculation is about 42.2 °C. The reason for the difference between the calculation and the measurement is that for the calculation, only the heat dissipation by the heat conduction from the compressor head is considered, while for the measurement, a cooling fan from the outside of the pressure vessel is used. In the future, in order to verify the calculation, the temperature of the compressor will be measured in a vacuum-insulated environment.

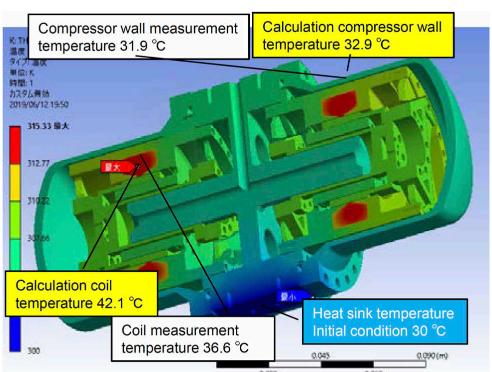
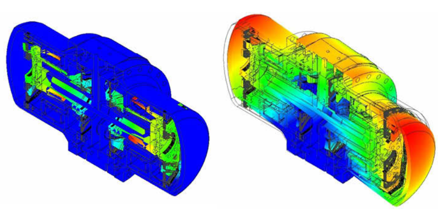


Figure 4. Heat transfer analysis results and measured temperature



(1) 852 Hz (2) 1680 Hz

Figure 5. An example of natural frequency analysis results.

Furthermore, it is important for cryocoolers used in space to withstand vibrations and shock during the launch of a satellite. Therefore, a mode analysis was performed with a fixed central part of the compressor and no viscosity from 1 to 2 kHz. Figure 5 shows an example of the calculation. It shows that the mode frequency for the entire compressor vibrating around the fixed part is 852 Hz, and the moving part oscillating around its center of gravity is 1688 Hz.

Verification of STC performance calculation program using new compressor

Based on these results, a new compressor has been made, and the performance of the compressor has been evaluated. Figure 6 shows a comparison between the new and the current compressors. This figure shows that the new compressor has no significant difference in weight and size compared with the current compressor. In addition, a performance comparison is shown when using a single-stage STC expander with the new compressor in Figure 7. The maximum cooling capacity is 3.2 W at 77 K with an initial gas pressure of 2.0 MPa, an operating frequency of 52 Hz, an electric input power of 50 W and an environmental temperature of 23 °C. This figure shows that the compressor and motor efficiencies are greatly improved to 80.7% and 84.5%, compared to 63% and 65.2% for the current compressor. In addition, with an electric input power of 100 W, a cooling capacity of 5.6 W at 77 K has been achieved. Since the expander is not optimized for the upper-said electric input power, the cryocooler performance can be further improved by optimizing the expander.

To design a PTC, the calculation accuracy of the code (ADISY) developed for an STC for high-temperature superconducting (HTS) motor cooling and a commercially available software, SAGE, was verified. Figure 8 shows a comparison between the calculation and the measurement results at 100 W electric input power using the new compressor. Although the compressor P-V work obtained by SAGE is slightly larger than the measured value, the calculated cooling capacity with both programs is close to the measurement results. Although the calculation is conducted with an STC, it is considered that the same tendency can be obtained with a PTC, qualitatively.

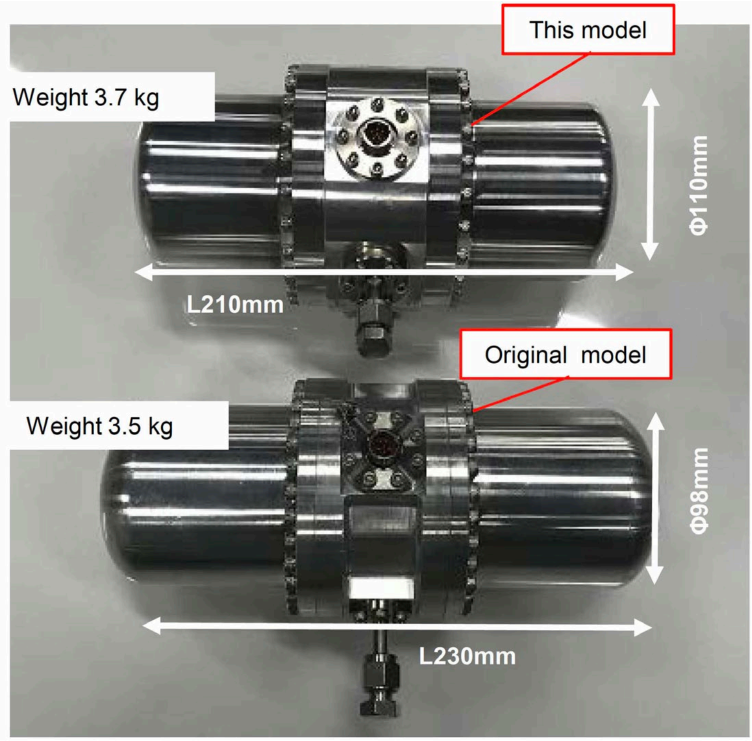


Figure 6. Comparison between the new and the current compressors

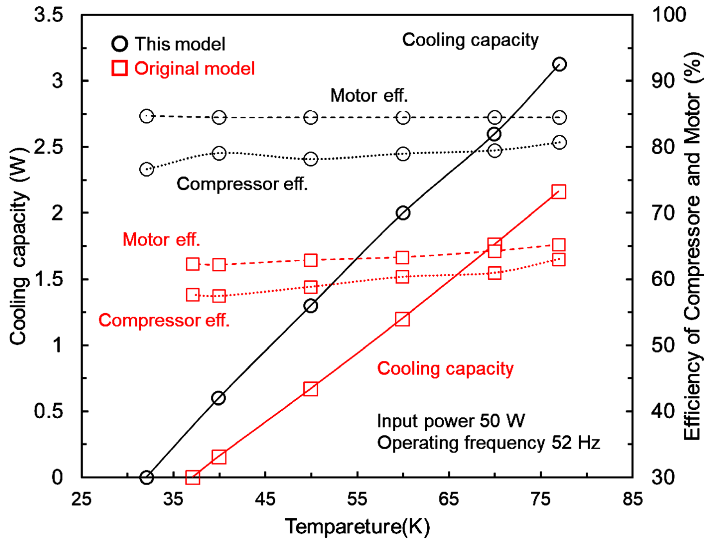


Figure 7. Performance comparison between the new and the current compressors.

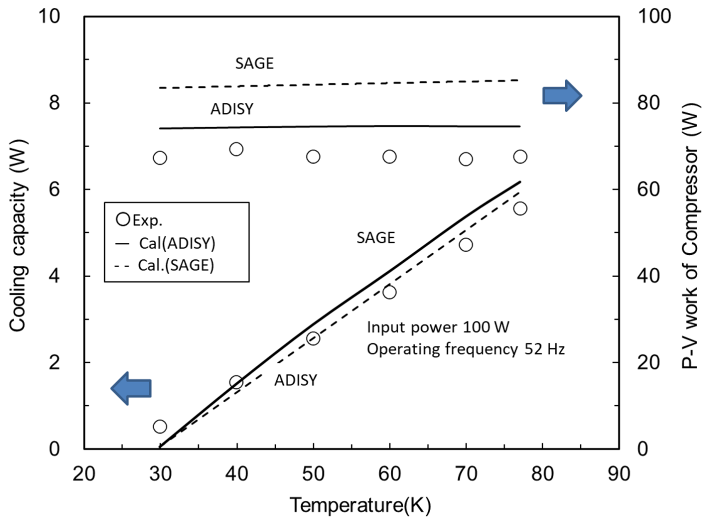


Figure 8. Comparison between the calculation and the measurement results at 100 W electric input power using the new compressor with STC

DESIGN AND PERFORMANCE EVALUATION OF PROTOTYPE PULSE TUBE CRYOCOOLER

Cooling test prototype pulse tube cryocooler

Since it is necessary to reduce the influence of vibration from the cryocooler on the sensor, an active balancer is attached to the STC expander. However, the driver for the balancer is very expensive, and the development lead time is very long. Furthermore, since the cylinder of an STC expander is thin, the weight load on the cold head is limited. Although a PTC expander is less efficient than an STC, it may solve the above problems owing to its elimination of moving parts. As with the STC performance calculation program, the PTC was designed and prototyped using the performance calculation code developed for a cryocooler to cool an HTS filter [1], and SAGE. Then, three types

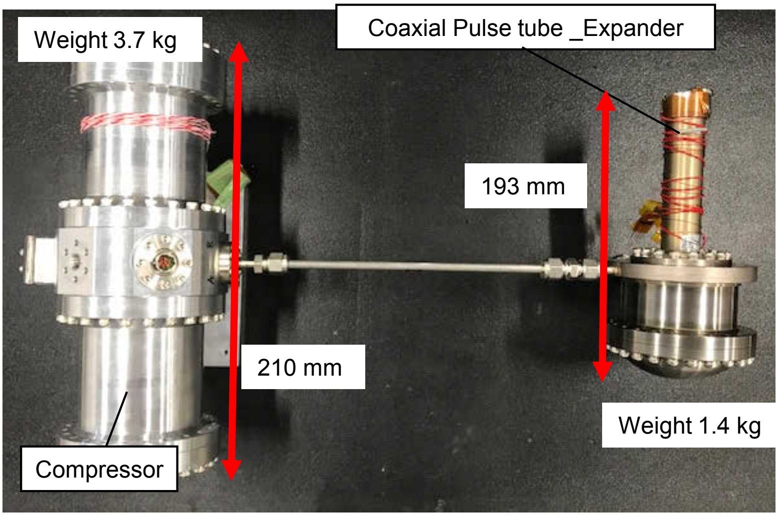


Figure 9. Photograph of a prototype co-axial pulse tube cryocooler.

of prototype expanders were built: in-line, U-shape and co-axial. Figure 9 and 10 show the photograph of a prototype co-axial pulse tube cryocooler and the cooling capacity of these expanders, respectively. It shows that the cooling capacities of all the prototype pulse tube expanders exceed the target value of 5 W at 77K, although there is a larger difference in the cooling performance at low temperatures. For the co-axial expander, a cooling capacity of 5.2 W at 77 K and a COP of 0.043 are obtained with a rated electric input power of 120 W and an operating frequency of 51 Hz. A cooling capacity of 6.3 W at 77 K was achieved with a maximum electrical input power 160 W.

Vibration measurement of cryocooler

Although it is not completely vibration-free, a PTC has significantly lower vibration than an STC due to the elimination of moving parts. The vibration of a PTC is mainly caused by an imbalance of parts. The imbalance between the left and right sides of the compressor can be adjusted and controlled by the feedback of a force sensor. To simplify the setup, vibration measurement was performed without any controller. Figure 11 shows a photograph of the measurement device.

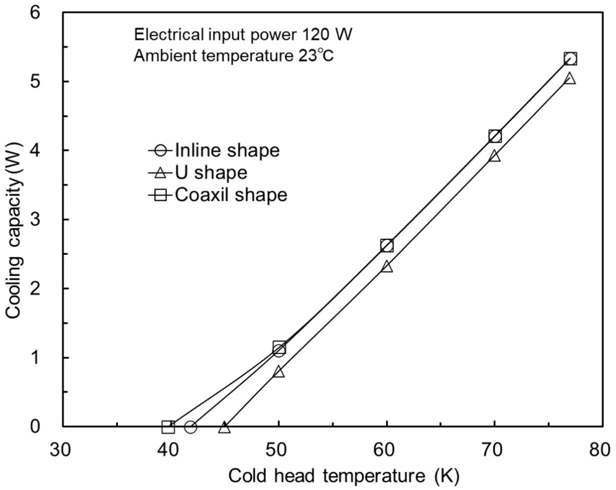


Figure 10. Cooling performance comparison of three types of pulse tube expanders.

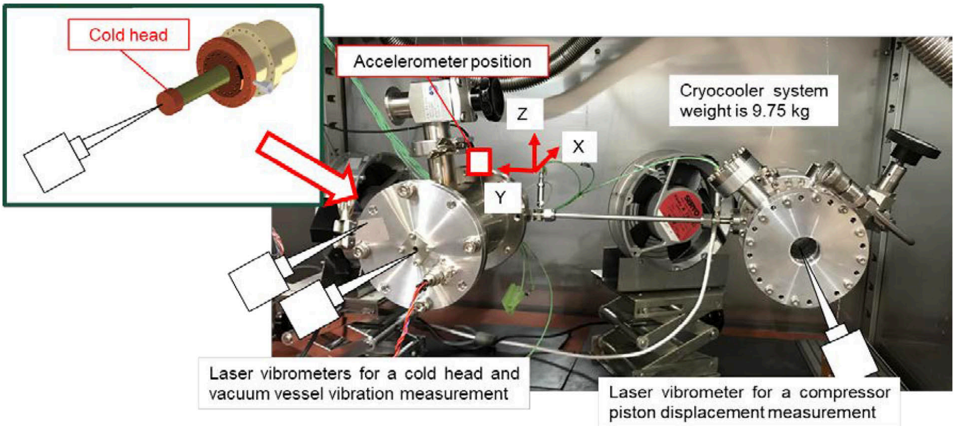


Figure 11. Photograph of vibration measurement when the refrigerator is suspended from the top with a fishing wire.

The measurement was performed using a laser vibrometer and an accelerometer. Both the displacement and the acceleration were measured. The vacuum pump was disconnected, the fan and constant temperature bath were turned off, and the pressure sensor was removed. Also, to minimize the influence of disturbance, the cryocooler was suspended using a fishing wire. Figure 12 and 13 show the displacement and acceleration measurement results, respectively, while the expander operates at 77 K. In these figures, the vibration amplitude of the cold head was 1.5 μm p-p in the axial direction and 0.5 μm p-p in the radial direction. The vibration amplitude is not completely synchronized with the pressure in the expander, nor is it synchronized with the axial direction and the orthogonal axis. Not only was the vibration due to pressure fluctuation picked up, but also the vibration due to disturbance (vibration from the compressor), and considered as the result. The maximum acceleration is 91.7 mm / sec^2 on the Y-axis, the total weight of the cryocooler system, including a vacuum vessel, is 9.75 kg and the maximum vibration force of the cryocooler is 894 mN in the Y-axis direction. When the acceleration of the compressor is measured, it is 140 mm / sec^2 (51Hz) in

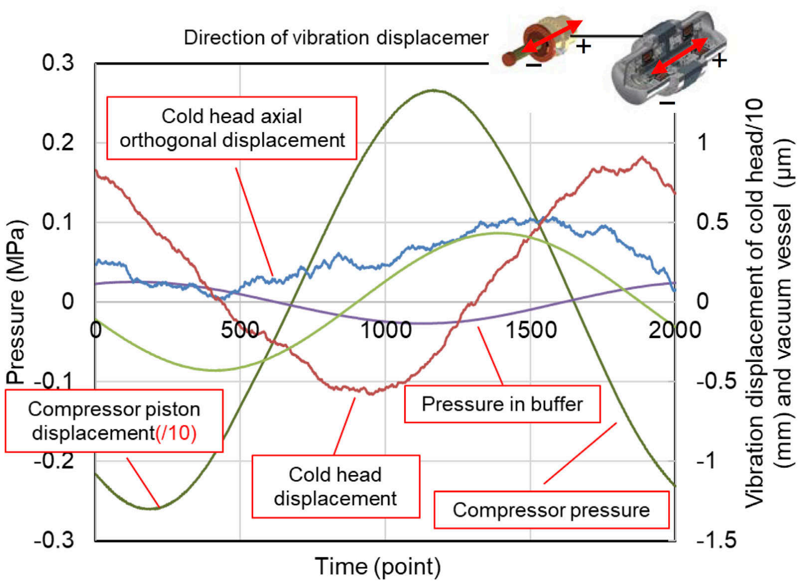


Figure 12. Vibration (displacement) measurement result.

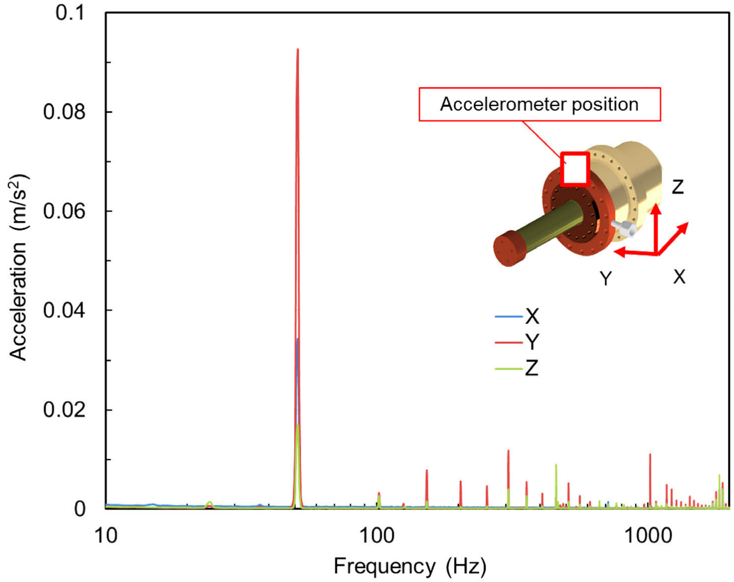


Figure 13. Acceleration measurement result.

the piston moving direction, Y-axis. It can be predicted that the left and right sides are not balanced and may affect the vibration of the expander. It is considered that the vibration of the expander can be reduced by suppressing the vibration of the compressor.

Furthermore, the connection tube was changed from a rigid SUS tube to a flexible one, and the positions where vibration was not easily transmitted to the expander were investigated. Figure 14 shows a photograph of a PTC connected by a flexible connecting tube and the results of the measured acceleration. In this figure, it shows that by using a flexible connection tube, the Y-axis becomes 60 mm / sec^2, which is reduced by about 2/3.

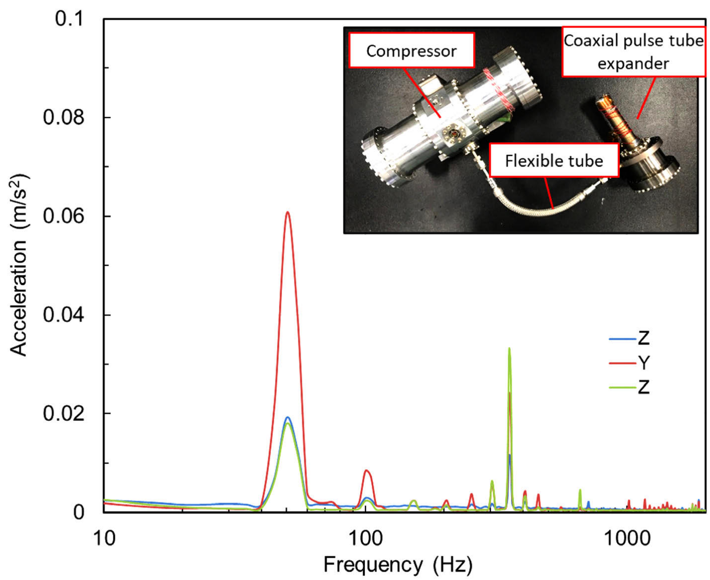


Figure 14. Acceleration measurement result using a flexible tube

SUMMARY AND FUTURE WORK

A high-efficiency compressor was designed and built for the purpose of increasing the cooling capacity of a single-stage STC mounted on a satellite, and its performance test was carried out. Although the rated input power was increased, the compressor and motor efficiencies were greatly improved by changing the motor configuration, and it was possible to have almost the same size and weight as the current compressor.

Also, a prototype co-axial PTC was designed, built and tested. As a result, a cooling capacity of 5.2 W at 77 K and COP 0.044 were obtained with an electric input power of 120 W. In addition, the vibration and acceleration of the expander were measured. The vibration amplitude of the cold head was 1.5 μm p-p in the axial direction and 0.5 μm p-p in the radial direction. The maximum acceleration was 91.7 mm / sec^2 in the axial direction. Accordingly, for the total weight of the cryocooler and vacuum vessel of 9.75 kg, the maximum vibration force was 894 mN. It is considered that this exciting force can be reduced by suppressing the vibration of the compressor.

In the next stage, it is planned to consider increasing the cooling capacity of a two-stage PTC using this single-stage PTC.

REFERENCES

1. Y. Hiratsuka, Y.M. Kang, "Development of a 1 to 5W at 80K Stiling Pulse Tube Cryocooler," *Cryocoolers 10*, Plenum Publishing Corp., New York (1999), pp. 149-155.