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Evaluation of Vibration Characteristics of a 1.5 W 4 K Pulse Tube Cryocooler with Improved First Stage Cooling Capacity

Ryoya Sato* **and Yosuke Matsumura**

Cryogenics Division, Precision Equipment Group, Sumitomo Heavy Industries, Ltd., Nishitokyo-shi, Tokyo, Japan

*E-mail: ryoya.sato@shi-g.com

Abstract. Pulse tube (PT) cryocoolers are extensively utilized in various applications, including dilution refrigerators for quantum computers and physical property measurement systems that require minimal mechanical vibration-induced noise. In the field of physical and chemical applications, there is a growing need for enhanced first stage cooling capacity. To address this demand, Sumitomo Heavy Industries (SHI) has developed RP-182C2S as an upgrade to our existing 1.5 W 4 K PT cryocooler, RP-182B2S. This upgrade offers a substantial improvement in first stage cooling capacity, increasing its specification from 36 W at 48 K to 42 W at 45 K, while maintaining the specific second cooling capacity and interface on the cylinder side. From a vibration standpoint, increasing the cooling capacity can potentially have negative effects on vibration characteristics. This is primarily due to factors such as the larger cylinder size and changes in operating pressure conditions. Another factor to consider is the alteration in the gas intake and exhaust direction of the cold head piping, transitioning from a horizontal design (used in 1.0 W 4 K PT cryocoolers) to a vertical design (implemented in 1.5 W 4 K PT cryocoolers). These modifications may also impact the vibration characteristics. Moreover, while vibration measurements of cryocoolers are typically conducted in room temperature environments, it is essential to perform such measurements in cryogenic environments to achieve more accurate and realistic results. In this study, we developed a test bench enables vibration measurements in a second stage condition at 4.2 K. We used this setup to conduct vibration measurement on RP-182C2S as well as RP-182B2S and RP-082B2S which served as the comparative cryocoolers. The evaluation results indicate that RP-182C2S demonstrates nearly identical vibration characteristics to RP-182B2S in terms of displacement and acceleration. Additionally, it was suggested that adjusting the direction of the piping can help mitigate vibration levels in a specific direction.

1. Introduction

PT cryocoolers can achieve cryogenic temperatures of around 4.2 K by means of the Gifford-McMahon (GM) cycle. However, in PT cryocoolers, the displacer found in GM cryocoolers is replaced by a helium gas element known as the gas piston. This gas piston is driven by both a rotary valve and a phase shifter, resulting in PT cryocoolers having the advantage of low mechanical vibration during operation. Particularly in the field of physics and chemistry, where mechanical vibration can adversely affect evaluation results [1]-[3], PT cryocoolers are extensively used due to their ability to minimize such vibrations. However, it should be noted that mechanical vibration resulting from fluctuations in helium gas pressure and rotary valves can still occur even in PT cryocoolers. As a result, ongoing research on reducing vibration remains an active area of study [4]-[6].

In recent years, quantum computing systems have gained significant attention in the field of physics and chemistry. Various methods are being explored for the working principles of quantum computers, many of which require cryogenic cooling. For example, the superconducting method uses dilution refrigerators, capable of reaching temperatures as low as approximately 10 mK. In this cooling process, PT cryocoolers play a crucial role in pre-cooling from room temperature to around 50 K and 4 K [7]. As the number of superconducting qubits is expected to increase in the future, the number of wires needed for measurement and control will also rise. However, this increase in the number of wires can introduce heat from room temperature. To mitigate the generation in thermal noise in superconducting quantum circuits, it is essential to have sufficient pre-cooling capacity at the first stage of PT cryocoolers. Unfortunately, increasing cooling capacity typically involves scaling up the cylinder size of PT cryocoolers, which can negatively impact on mechanical vibration characteristics. To address this challenge, SHI has developed a new 1.5 W 4 K PT cryocooler that significantly improves the first stage cooling capacity without changing the cylinder section interface design of the existing model. Additionally, SHI has conducted vibration measurements under actual cryogenic operating conditions to compare the new cryocooler with existing models.

2. Outline of a new SHI 1.5 W 4 K PT cryocooler, RP-182C2S

Figure 1 shows the depiction of the new SHI 1.5 W 4 K PT cryocooler "RP-182C2S", as well as a comparison of its interface with RP-182B2S model. RP-182C2S comprises three main components: the cold head (CH), the valve unit (VU), and the buffer tank. The CH is connected to the VU with two ϕ 3/16" x 0.75 m flexible gas lines and one ϕ 1/2" x 0.75 m flexible gas line, and to the buffer tank with one ϕ 5/16" x 1 m flexible gas line. The VU, on the other hand, is connected to a compressor that supplies high pressure helium gas using two ϕ 1" x 20 m flexible gas lines.

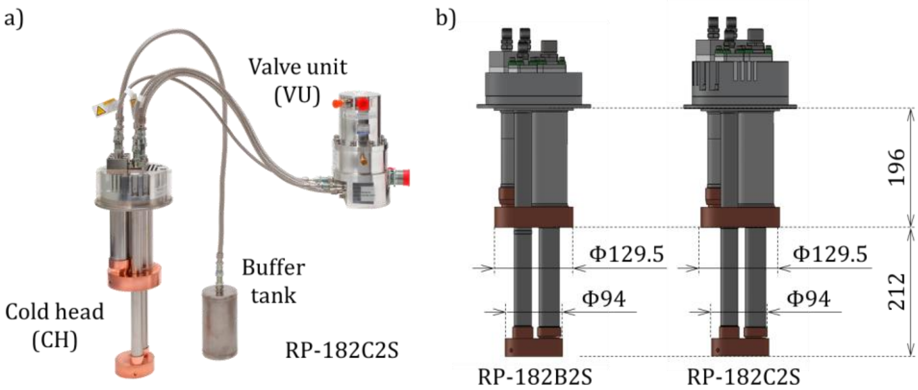

Figure 1. a) Depiction of RP-182C2S, comprising the CH responsible for generating cold, the VU containing a rotary valve, and the buffer tank. b) Interface comparison with RP-182B2S, showing compatibility in terms of cylinder length and stage outline.

Comparing the interface with RP-182B2S, the cylinder length from the base flange to the first stage and from the first stage to the second stage are identical, and the outer diameter of the first and second stage are also identical, so the interface on the low temperature side is compatible with the existing 1.5 W 4 K model.

Table 1 provides a list of the main specifications of both RP-182C2S and RP-182B2S. The most siginificant difference is that the first stage cooling capacity has been increased from 36 W at 48 K to 42 W at 45 K. However, the second stage cooling capacity remains the same for both models. It is noteworthy that both models use the same water-cooled compressor unit, F-100, resulting in equivalent power consumption.

Figure 2 depicts the heat load maps of both RP-182B2S and RP-182C2S. The maps show a significant improvement of the first cooling capacity, particularly in areas where the heat load exceeds approximately 20 W. Additionally, there is an improvement in the second stage cooling capacity in regions where the heat load is above approximately 4 W. At 50 Hz, a typical cooling capacity of 42 W at 40.8 K was achieved at the first stage and 1.5 W at 3.94 K at the second stage, with an input power of 11.6 kW. Similarly, at 60 Hz, a cooling capacity of 42 W at 38.1 K was

Table 1. Specifications of RP-182B2S and RP-182C2S.

	RP-182B2S	RP-182C2S
First stage cooling capacity	36 W at 48 K	42 W at 45 K
Second stage cooling capacity	1.5 W at 4.2 K	1.5 W at 4.2 K
Cooldown time to 4 K	< 60 min*	< 60 min*
No-load temperature	< 2.8 K*	<3.0 K*
Power consumption (50Hz/60Hz)	11.8 kW*/14.5 kW*	11.8 kW*/14.5 kW*
Compressor	F-100	F-100
Mass	CH: approx. 18 kg* VU: approx. 11 kg*	CH: approx. 19 kg* VU: approx. 11 kg*
Cold head maintenance interval	20,000 hrs	20,000 hrs

*Reference number

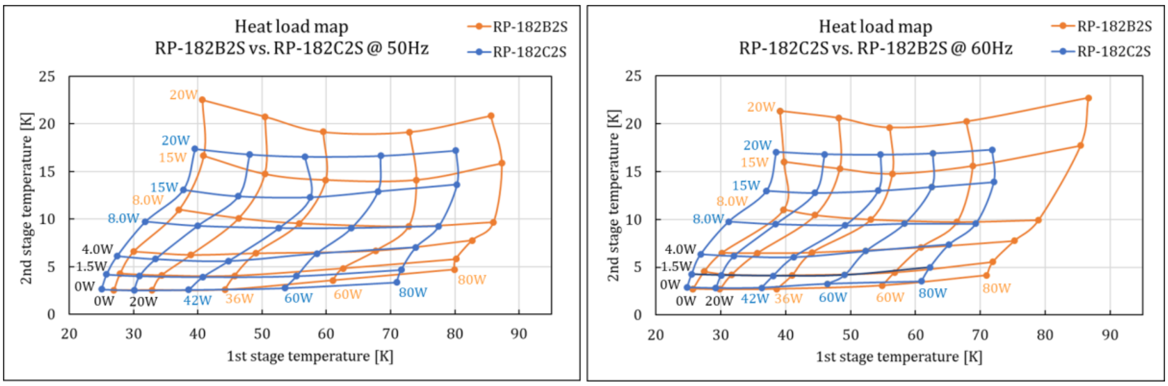

Figure 2. Heat load maps of RP-182B2S and RP-182C2S at 50 Hz/60 Hz.

achieved at the first stage and 1.5 W at 4.10 K at the second stage, with an input power of 14.4 kW. These improvements indicate the increased efficiency and capability of RP-182C2S compared to RP-182B2S.

3. Measurement method of vibration characteristics

In this paper, to evaluate the vibration characteristics of RP-182C2S, vibration measurements were conducted with two other types of PT cryocoolers: RP-182B2S and RP-082B2S, which is a 1.0 W 4 K PT cryocooler. The test setup of vibration measurements and the combination of the compressor and the CH are shown in Figure 3. The PT cryocooler is installed in the vacuum chamber, which is rigidly connected to a frame designed to consider the natural frequency of the cryocoolers. The vacuum vessel is equipped with hermetically sealed ports that allow for the wiring of accelerometers, temperature measurement sensors, and heaters, as well as view ports for measuring the displacements of the cooling stage using laser displacement meters. The first stage is equipped with mylar insulations and a copper radiation shield, both of which have view ports. To ensure accurate measurements in cryogenic temperatures, accelerometers that are guaranteed to operate in such environments were selected. The connection configuration from

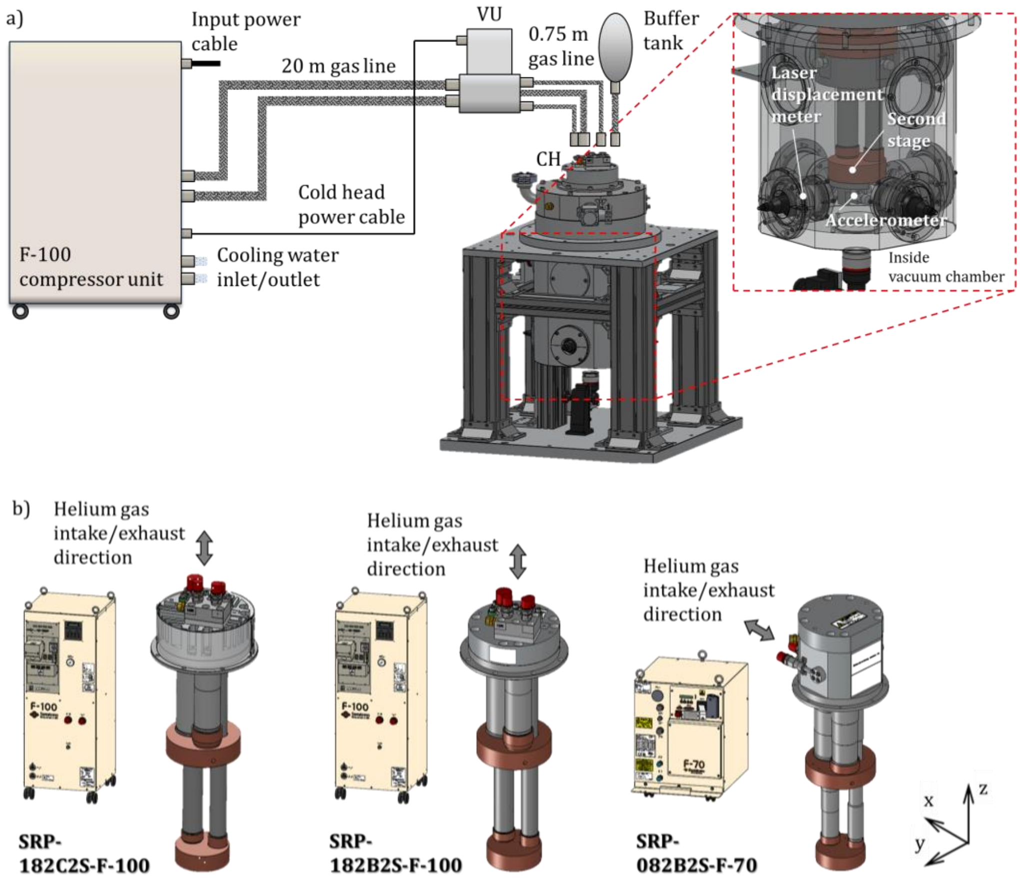

Figure 3. a) Configuration of vibration measurement tests. Accelerometers and laser displacement meters are installed in the vacuum chamber to enable vibration measurements in cryogenic environments. b) Combination of the compressor and the CH. X, y and z coordinates were set to standardize the positional relationship between the pulse tube and the regenerative tube across different models.

the compressor to the CH was identical to the standard configuration of each model. In the vibration measurement test setup, the applied heat loads were adjusted from the specified values to maintain a first stage temperature of 45 K and a second stage temperature of 4.2 K. This adjustment was made considering the higher radiation heat due to the presence of view ports. Additionally, the filling pressure and steady-state operating pressure remained the same as the standard conditions. We included RP-082B2S, which has a different cooling capacity, for comparison with RP-182C2S. The reason for this is that the piping supplying helium gas is parallel to the cooling stage in RP-082B2S, whereas it is in a vertical direction for the 1.5 W 4 K model. We wanted to evaluate the effect of this piping direction on the vibration characteristics.

4. Comparison of vibration characteristics

4.1 Comparison with existing 1.5 W PT cryocooler, RP-182B2S

Figure 4 shows the comparison of the displacement and acceleration vibrations of the second stage of RP-182C2S and RP-182B2S cryocoolers. In terms of displacement, we observed peak-to-peak values of ±13.2 μm, ±4.8 μm and ±12.2 μm in the x, y and z directions for RP-182B2S, and ±13.4 μm, ±4.4 μm, and ±12.0 μm for RP-182C2S. The displacement varied with the frequency of helium intake and exhaust, and the difference in displacement between the x and y directions was due to the asymmetric shape of the cryocoolers.

Regarding acceleration, we observed values of ±0.86 m/s^2, ±0.67 m/s^2 and ±0.78 m/s^2 for RP-182B2S, and ±0.86 m/s^2, ±0.60 m/s^2 and ±0.68 m/s^2 for RP-182C2S. The acceleration peaks twice in one cycle, once during intake and once during exhaust.

During the development of RP-182C2S, improvements were made to reduce cryocooler losses, but no changes were made to the cylinder geometry or operating pressure conditions. Therefore, we consider that the vibration characteristics of RP-182C2S are almost equivalent to those of RP-182B2S.

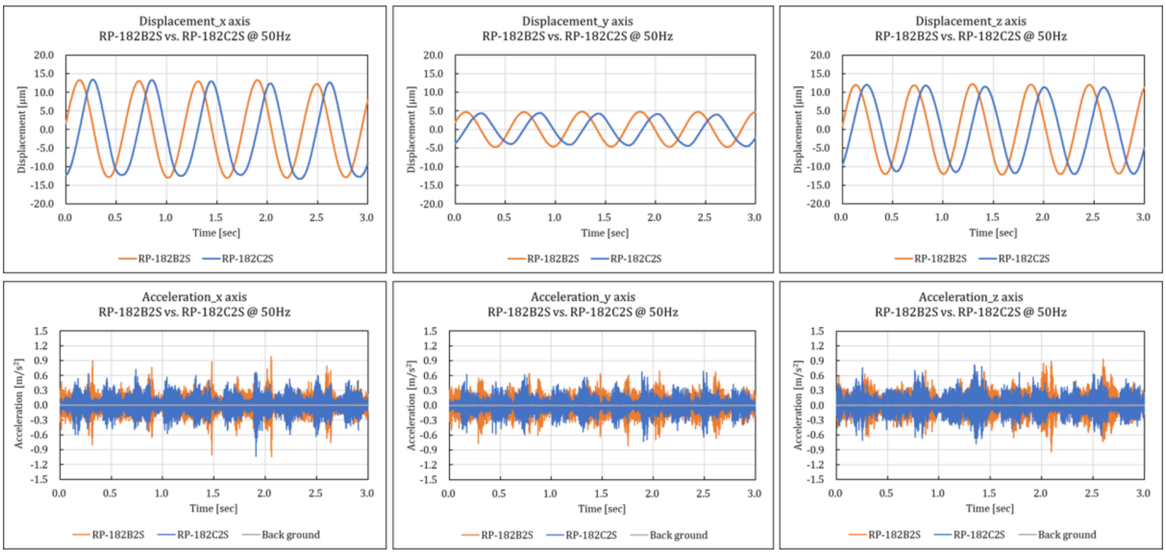

Figure 4. Comparison of the displacement and acceleration of the second stage of RP-182B2S and RP-182C2S in each direction at 50 Hz. Displacements are shown as a time series of measurements over a 3-second period. Accelerations are also shown as a time series measurement result with, the background representing the cryocooler shutdown.

4.2 Comparison with 1.0 W PT cryocooler, RP-082B2S to evaluate the effect of piping direction

Figure 5 compares the acceleration vibration of RP-082B2S and RP-182C2S cryocoolers. Overall, the vibration level of RP-182C2S is smaller than that of RP-082B2S in x direction, although there are some differences in the trend in each frequency band. This trend can be influenced by the direction of the piping that supplies helium gas to the cryocoolers. Since there is some degree of freedom in the direction of the gas piping, it suggests that it may be possible to reduce the acceleration vibration level in a specific direction, making the cryocoolers more suitable for a customer's equipment.

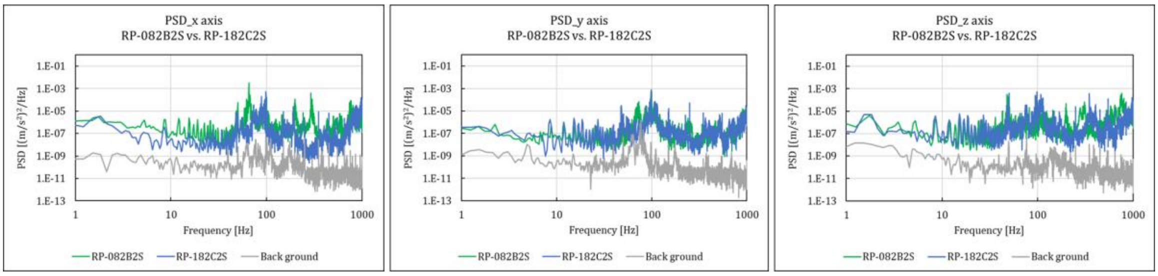

Figure 5. Comparison of the accelerations of the second stage of RP-082B2S and RP-182C2S for in each direction at 50 Hz. Accelerations are shown as a power spectral density (PSD) with the background.

5. Conclusions

To meet the demands of the physical and chemical application markets, we developed a new 1.5 W 4 K PT cryocooler with improved first stage cooling capacity while maintaining the second stage cooling capacity and the interface. To assess the effect of this improvement on vibration characteristics, vibration measurements were conducted under cryogenic conditions. The results confirmed that the vibration characteristics of the improved cryocooler are equivalent to those of the current 1.5 W 4 K PT cryocooler. This means that we successfully enhanced the cooling capacity of the first stage without any negative impact on the vibration characteristics. Furthermore, the comparison to RP-082B2S suggested the possibility of reducing vibration levels in specific directions by changing the direction of the gas piping. This indicates that there is potential to further optimize the vibration characteristics to better suit the requirements of customer equipment.

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