Reliability Evaluation of Stirling Cryocooler for an Electric Vehicle High Temperature Superconducting Motor System

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ABSTRACT

Due to the performance improvement of high temperature superconducting wires, the development of superconducting motors has been actively developed. To demonstrate the efficiency improvement of an electric vehicle driven by a superconducting motor, development of superconducting motors and cooling systems has been performed by the joint research of Sumitomo Heavy Industries, Ltd. (SHI) and Sumitomo Electric Industries, Ltd. (SEI). The results of the actual vehicle tests and simulations showed that it is possible to improve the efficiency by about 10% compared to a conventional electric motor. In this project, SHI developed a high-efficiency Stirling cryocooler with a cooling capacity of 151 W at 70K and a compressor input power of 2.15 kW with a corresponding COP of 0.07.

More compact, efficient and reliable cryocoolers are required for the commercial use of a superconducting bus. In this paper, the investigation of the reliability of the cryocooler is introduced. The operation system, the safety measures, and the long-term operation and environmental performance test results will be presented.

INTRODUCTION

High Temperature Superconducting Motor System Development Project

After the high temperature superconductivity (HTS) was discovered, the application of HTS devices has been studied in many fields. The application of HTS equipment is possible for commercial use. In addition, superconducting technology has been attracting attention as a means to resolve environmental issues such as energy conservation and carbon dioxide emissions reduction. In the field of transportation, efforts have been made to improve the efficiency of an electric vehicle. Because of its high efficiency in at low speeds, a superconducting motor is a potential choice for a bus, which requires frequent stops.

Recently, the development of a superconducting motor and cooling system has been completed by the joint research of Sumitomo Heavy Industries, Ltd. (SHI) and Sumitomo Electric Industries, Ltd. (SEI). This project aims to improve the overall electric efficiency of the motor by 10% relative to a conventional electric motor. The motor's superconducting state is maintained by circulating liquid nitrogen which is cooled by a cryocooler. To improve the total efficiency of a superconducting motor system, it is vital to improve cryocooler performance. Thus SHI has been developing a high-efficiency Stirling cryocooler for such superconducting motor systems.

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Stirling Cryocooler for Superconducting Motor System

Owing to its high cooling capacity and efficiency, a Stirling cryocooler has been developed for cooling a superconducting motor. It is possible to achieve a high efficiency at liquid nitrogen temperature range since there is no valve loss in a Stirling cryocooler and low temperature space P-V work can be recovered. Figure 1 shows a photograph of the cryocooler under discussion. The schematic cross-section diagram of a Stirling cryocooler is shown in Figure 2. A split-type Stirling cryocooler was selected because the compressor and expander can be arranged independently in the motor room. Helium gas is charged in the cryocooler and the initial gas pressure is 1.7 MPa. The compressor consists of a moving-magnet type motor and two opposed pistons which are driven by the linear motor. The moving cylinders are guided by flexure bearings, which can maintain clearance of several micro meters between the pistons and cylinder. A water-cooled heat exchanger is built in the outer body of the compressor to transfer heat generated by the motor. The expander consists of a cold-head, a regenerator, a heat exchanger and a free-piston type displacer. The displacer piston and the regenerator are coaxially arranged. The displacer piston is also guided by flexure bearings. The regenerator is packed with thousands of stainless-steel screens. The heat exchanger in the expander is a shell and tube type and is also water-cooled. To suppress vibration from the displacer, a vibration absorber is attached.

As to the cryocooler performance, a cooling capacity of 151 W at 70K with a compressor input power of 2.15 kW and cooling water temperature of 30 ℃, corresponding COP of 0.07, and a no-load temperature of 33 K, has been achieved[1].

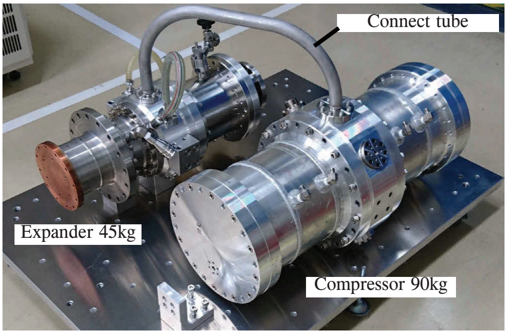

Figure 1. Photograph of Stirling cryocooler developed.

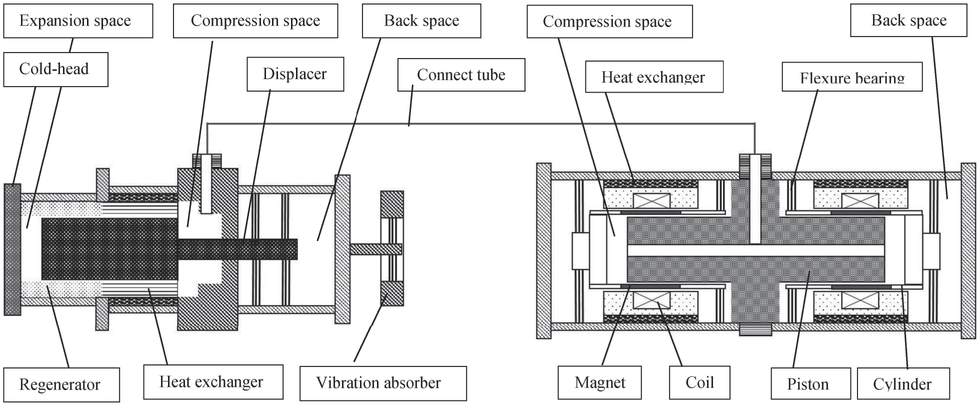

Figure 2. Schematic cross-section diagram of the expander and compressor.

Actual Vehicle Test

After the cryocooler performance was tested, the cryocooler and superconducting motor unit were mounted in an electric bus, and preliminary driving tests were conducted. The cryocooler was driven by an inverter power source and the input power was controlled by a proportional–integral–derivative (PID) algorithm to maintain a constant cold-head temperature. For safe operation of the superconducting motor system, the inverter power source is designed to shut-down automatically if any abnormality is detected. For example, the voltage and current levels, the cryocooler outer wall temperature and the displacer piston stroke are monitored by a control system. Cooling water for the heat exchanger is supplied from the electric bus radiator. Actual bus running test and simulation of the running pattern were carried out. As a result, it was found that the efficiency can be increased by about 10% compared to a conventional motor if the weight of a superconducting motor is the same as that of a conventional motor[2].

RELIABILITY EVALUATION

For practical use of a superconducting motor, high reliability and safety is also required. Some experiments on the reliability evaluation have been conducted with the afore-mentioned cryocooler. In this paper, results of long term operation and vibration tests will be introduced.

Long Term Operation Test

In the practical use of a superconducting motor, the cryocooler will be continuously operated for several years in order to suppress the liquid nitrogen boil-off. Therefore, the cryocooler is required to maintain its cooling capacity over thousands of hours. After a short-term vacuum baking, the cryocooler has been operated at a lowest temperature of 33K for about 5,000 hours to detect potential initial failures. Initially, the cryocooler was operated with a cooling water of 30℃. In order to investigate the performance under severe conditions, the cooling water temperature was changed to 50℃ after 2,500 hours operation. The results are shown in Figure 3. As a result, the cooling capacity decreased 4.5% compared to that at the initial status and no load temperature rose about 3.5K. Mechanical factors and contamination are considered as causes of the performance degradation. Measures and isolation of performance degradation factors is under considering at the moment and will be solved in near future.

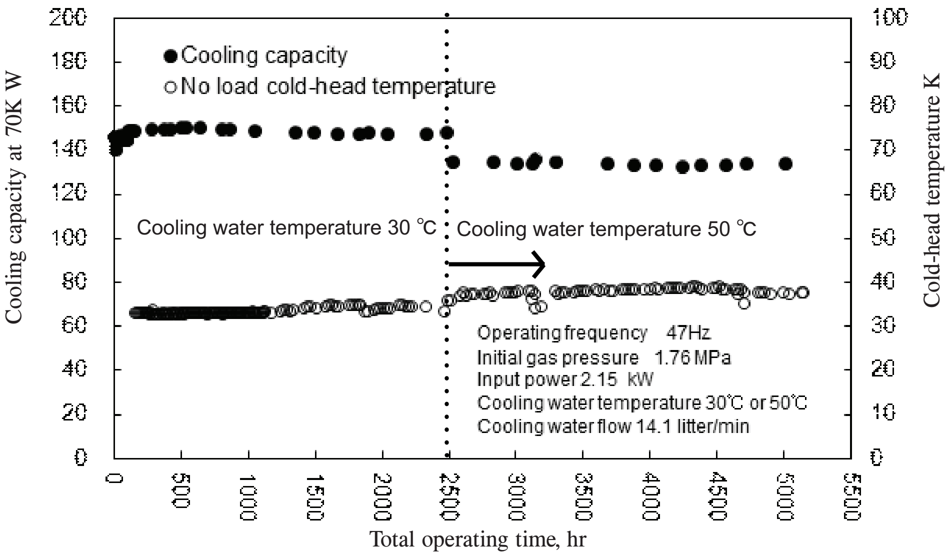

Figure 3. Experimental results of long term operation test.

Vibration Test

As an automotive cryocooler, it is important that the impact from road and cyclic vibration from the motor be considered in the reliability evaluation. In order to make the cryocooler more robust against vibration, it is necessary to measure the impact pattern, simulate the vibration mode and conduct a vibration test. Some simple vibration tests were conducted to measure the basic anti-vibration performance and vibration failure modes of the cryocooler. Figure 4 shows a photograph of the cryocooler unit mounted on a vibration exciter. The cryocooler was mounted as close to the same orientation as the actual vehicle test condition as was possible. Figure 5 explains the definition of the vibration direction and position of the acceleration sensors. The acceleration sensors were attached to the cryocooler body at four points. The vibration of the moving parts of the cryocooler (cylinder in the compressor, the displacer in the expander and the vibration absorber) was also measured through view ports by laser vibration detectors.

First, a random vibration test was performed to investigate the natural frequency and response magnification of the cryocooler body. A random vibration tests includes frequency components of

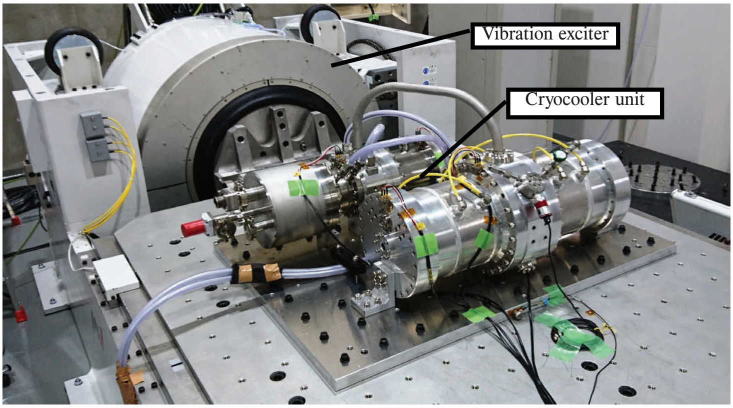

Figure 4. Photograph of cryocooler unit mounted vibration exciter.

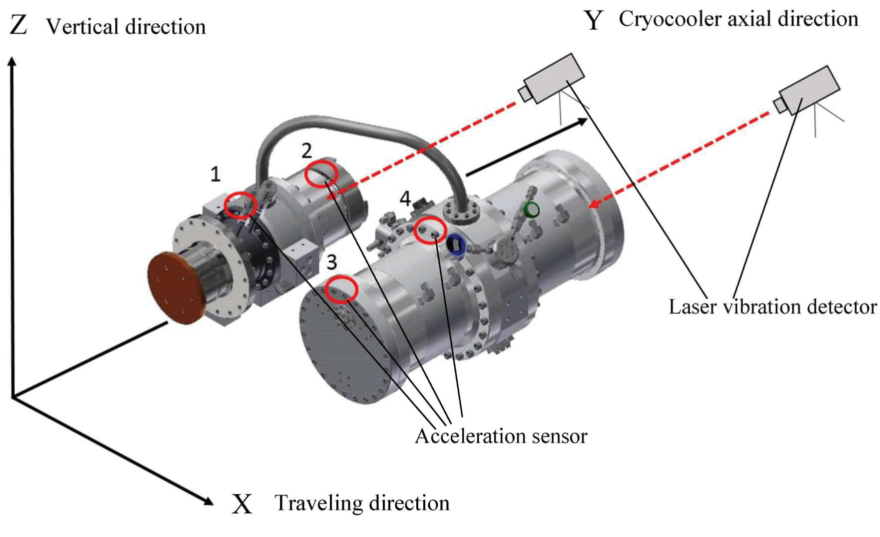

Figure 5. Three dimensional diagram of cryocooler and definition of the vibration directions and position of acceleration sensors.

10 to 1000 Hz which is exerted on the cryocooler. This test was conducted without operating the cryocooler. Figures 6, 7 and 8 show the measurement results of the response magnification factors in the X-axis (traveling direction), Y-axis (cryocooler axial direction) and the Z-axis (vertical direction), respectively.

Second, the natural frequency and the response magnifications of the moving cylinders in the compressor and the displacer in the expander and vibration absorber were measured. A sinusoidal vibration of 10 to 200 Hz and 0.5grms acceleration in the axial direction was applied to the cryocooler. The vibration of the cryocooler body and the moving parts was measured simultaneously using the two laser vibration detectors. The test was also conducted without operating the cryocooler. Figure 9 shows the response magnification and the phase with respect to the input of the compressor moving cylinder. A natural frequency of 33.1 Hz was observed and the maximum response magnification was about 10.8. Figure 10 shows the response magnification and the phase of the expansion displacer. As shown in Figure 10, the response magnification has a broader peak in comparison to the compressor. A natural frequency of 48.2 Hz was observed and the maximum response magnification was about 2.7. Figure 11 shows the measurement results of the response

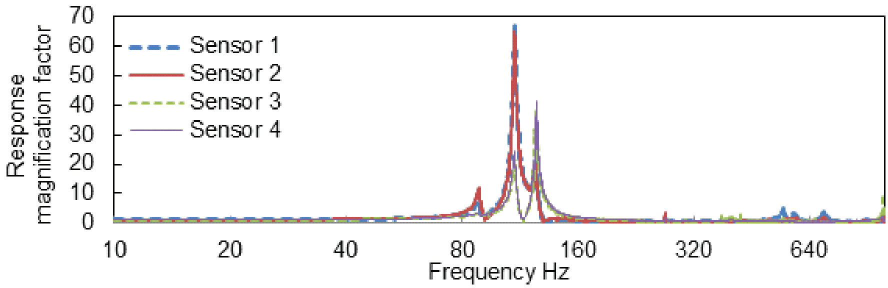

Figure 6. The response magnification factor of X-axis (traveling direction).

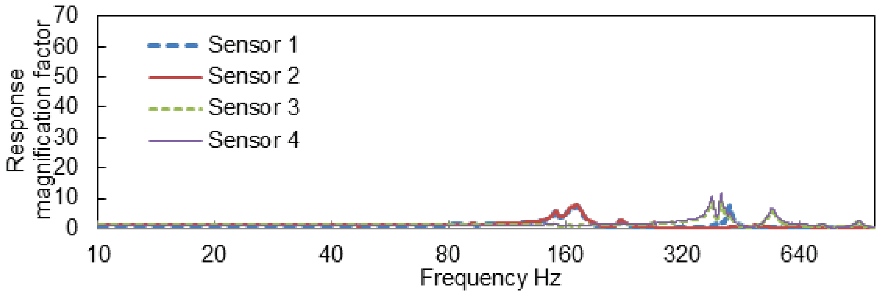

Figure 7. The response magnification factor of Y-axis (cryocooler axial direction).

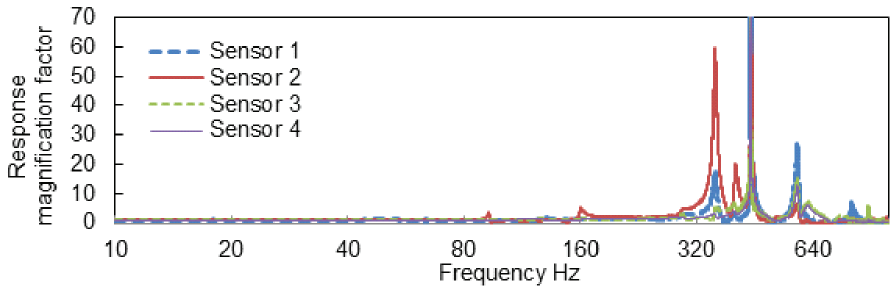

Figure 8. The response magnification factor of Z-axis (vertical direction).

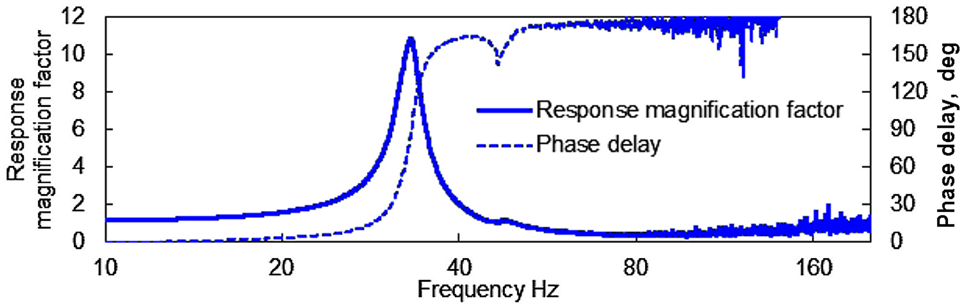

Figure 9. The response magnification and the phase delay of the compressor moving cylinder.

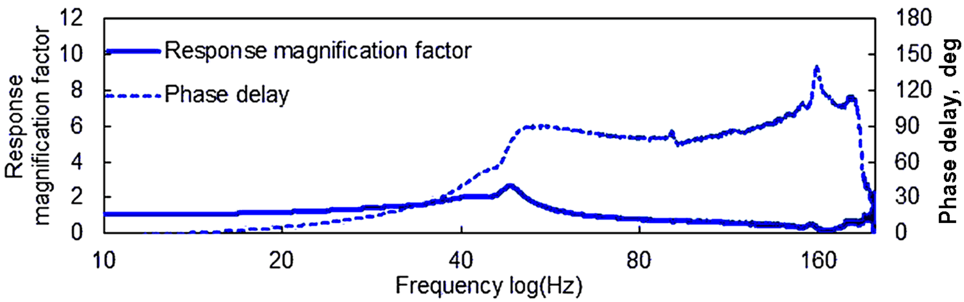

Figure 10. The response magnification and the phase delay of the displacer in expander.

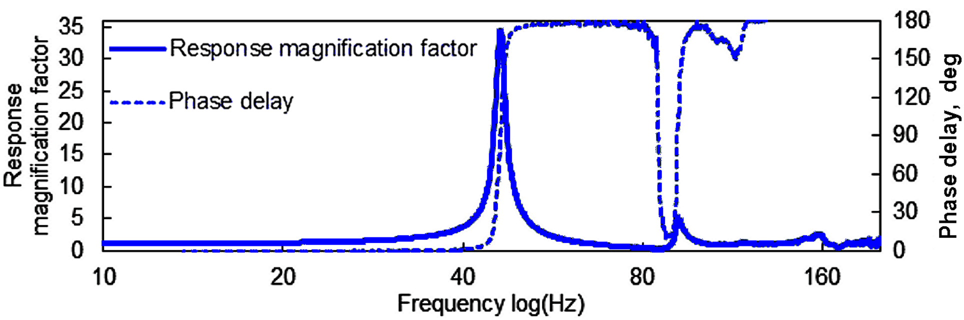

Figure 11. The response magnification and the phase delay of the vibration absorber.

magnification and the phase of the vibration absorber. As shown in Figure 11, the response magnification has an obvious peak at a natural frequency of 46.2 Hz and the maximum response magnification was about 34.6. The comparison of the test results and the natural frequency analysis which was calculated in advance is shown in Table 1. Differences between analysis and experimental results were considered to be due to imperfections in the analysis model, such as the viscosity of the gas and the constraint conditions. The measurement results will be utilized as data for next vibration analysis in our future work and will be feedback to the next design step.

Finally, the cooling capacity reduction rate due to vibration during cryocooler operation, was measured. The reduction rate was measured while a sinusoidal wave acceleration of 1 g in the range of 10 to 100 Hz was applied to the cryocooler. However, in the axial direction of the cryocooler, the displacer knocked the cylinder wall around 33 Hz when 1 g vibration was applied to. Therefore, for the axial direction, 0.3 g vibration test with full output and 1 g vibration test with 50% output of cryocooler, were conducted. Figure 12 shows the cooling capacity reduction rate at each frequency compared to that under no vibration. As a result, impact on cooling capacity due

Table 1. The comparison of the test results and the natural frequency analysis.

Item	Experimental results	FEM model analysis
Moving parts of compressor	33.1 Hz	20.2 Hz
Moving parts of expander	48.2 Hz	58.3 Hz
Vibration absorber	46.2 Hz	40.1 Hz

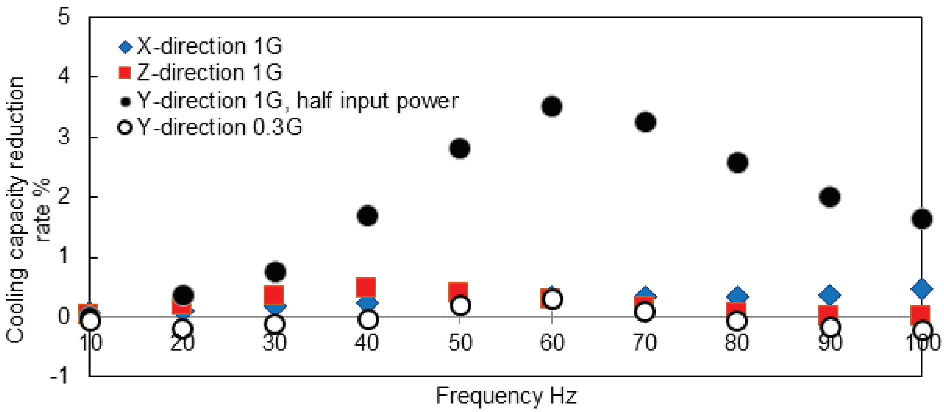

Figure 12. The cooling capacity reduction rate at each frequency.

to vibration was found to be small in the radial direction of the cryocooler (X-axis and Z-axis). In the cryocooler axis direction (Y-axis), cooling capacity reduction rate reaches its maximum around a vibration frequency of 60 Hz. The reason for the performance degradation around 60 Hz is still under investigation. Causes of knocking between the displacer and the cylinder wall around 33 Hz may affect the displacement and phase of the displacer and the cylinder wall. Figure 13 shows the state of the transmitted vibration to the displacer and the cylinder from vibration exciter. Table 2 shows the response magnification and the phase delay of the cryocooler in each frequency. With this information, the vibration of the displacer and the cylinder wall at each frequency are shown in Figure 14. In the low frequency range, for example around 10 Hz, the displacer will not knock the cylinder wall since there is no phase difference between the center position of the displacer and the cryocooler wall despite the large displacement. On the other hand, the displacer will also not knock with the cylinder wall since the vibration amplitude around 100 Hz is quite small. In the intermediate region, there is a risk of the displacer knocking. Since the natural frequency of the cryocooler's compressor cylinder is 33.1 Hz, the stroke of the compressor cylinder is increased in this frequency region. Hence it is believed that the stroke of the displacer is increased due to an increase in the compressor net input power.

Table 2. Response magnification and phase delay of the cryocooler in each frequency.

	G_1	G_2	G_3	G_4	θ_1 [deg]	θ_2 [deg]	θ_3 [deg]	θ_4 [deg]
10 Hz	1	1	1	1	0	0	0	0
33 Hz	1	1	4.97	1.58	0	0	90	23
100 Hz	1	1	0.33	0.66	0	0	172	79

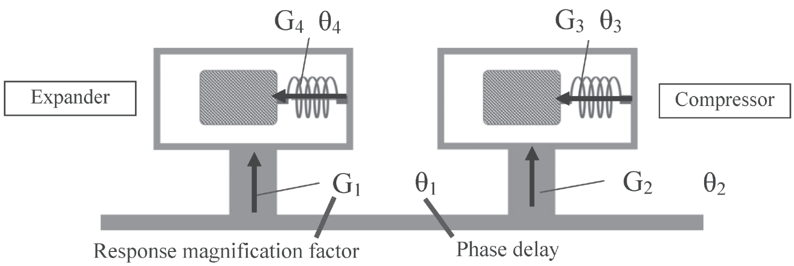

Figure 13. The state of the transmitted vibration.

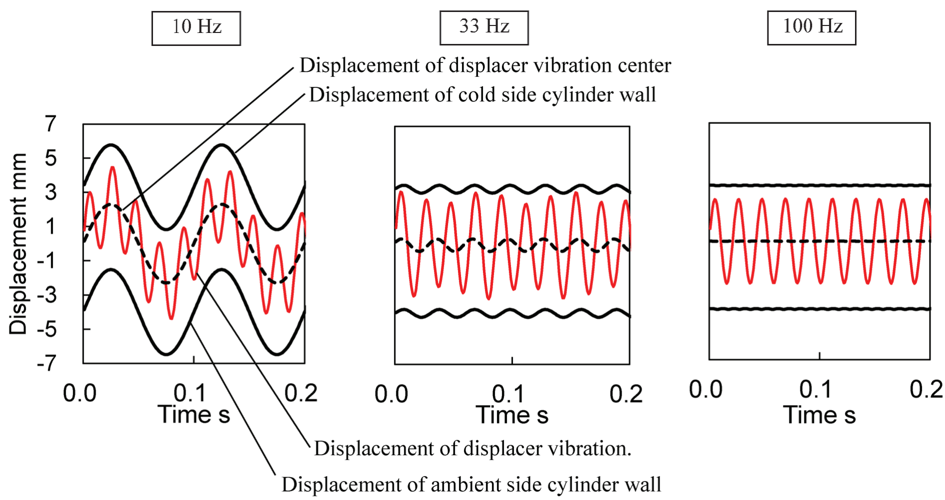

Figure 14. Vibrations of the displacer and the cryocooler wall.

SUMMARY AND FUTURE WORKS

This paper reports the reliability evaluation test results of a cryocooler for cooling a superconducting motor system. The cooling system is confirmed to be operated safely. The decrease in the cooling capacity was only a few percent after the system was continuously operated over 5,000 hours. Vibration tests were conducted, and the basic performance of the vibration resistance was obtained. In the future, a contamination measurement and anti-vibration design is scheduled to be performed.

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