Performance of vibration-free pulse tube cryocooler system for a gravitational wave detector

T. Haruyama, T. Tomaru, T. Suzuki, T. Shintomi, N. Sato, A. Yamamoto, Y. Ikushima*, R. Li*, T. Akutsu**, T. Uchiyama** and S. Miyoki**

KEK, High Energy Accelerator Research Organization, 1-1, Oho, Tsukuba 305-0801, Japan,
*Sumitomo Heavy Industries Ltd., 2-1-1 Yato, Nishitokyo, Tokyo, 188-8585, Japan
**Institute for Cosmic Ray Research (ICRR), The University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba, 277-8582, Japan

A pulse tube cryocooler system with a quite low vibration level has been developed for a gravitational wave detector. The origin of two types of vibration in a cryocooler system was identified, and a vibration-reduction method has been developed. A thermal link by using bundles of thin pure aluminum wires was applied for the vibration reduction at the cold stages, and a bellows was used for vibration reduction at the cold head. A cryocooler system with vibration of 50 nm in the Z-direction at the vibration reduction stage, and with a cooling power of 0.4 W at 4.2K and 15 W at 45 K has been developed. An overall vibration level was also confirmed as being identical with that of the seismic level at Kamioka mine. Results of development and the final performance of a vibration-free cryocooler system are presented.

INTRODUCTION

A feasibility study for the Large-scale Cryogenic Gravitational wave Telescope (LCGT) project has been promoted in Japan [1]. At present, a proto-type system, the Cryogenic Laser Interferometer Observatory (CLIO), is under construction in Kamioka mine, Japan [2]. To enhance the sensitivity of the gravitational wave detector, the sapphire mirrors should be cooled down around 20 K by using a cryocooler. Since the mirrors are extremely sensitive to vibrations, it is required that the vibration of the cryocooler must be reduced to the same level as that of the seismic vibration in Kamioka mine where the LCGT is expected to be installed. Then, one of the key technologies for realizing the LCGT project is the development of a cryocooler cooling system with a quite low vibration level.

We have investigated the origin of vibration in a pulse tube cryocooler system with the measuring method described in Ref.3, and found that there are two different origins of vibration in the cryocooler [3]. Based on the commercial two-stage pulse tube cryocooler, SRP-052A, by Sumitomo Heavy Industries, ltd., a vibration-free cryocooler system, which can reduce these two types of vibration, has been developed. In this paper, the origin of the vibration in a pulse tube cryocooler system, the vibration reduction method, the achieved performance of cooling power and vibration level, and the progressing test overview is reported.

ORIGIN OF VIBRATIONS IN A CRYOCOOLER

A measurement of the vibration in a pulse tube cryocooler has been carried out by using optical sensors; it was found that there exist two different vibrations in the cryocooler [3]. The first vibration is an intrinsic one at the cold stages of the cryocooler, which originates in a pressure wave inside of the pulse tube and the regenerator. The second one is vibration at the cold head of the cryocooler that mainly originates in the rotary valve and compressor. Regarding the first intrinsic vibration, the level at the cold stage is almost comparable between a pulse tube cryocooler and a GM cryocooler. The typical vibration level at the cold stage is about ~10 μm at 1 Hz. On the other hand, the second one, the acceleration level at the cold head of a pulse tube cryocooler, is about two orders of magnitude smaller than that of the GM cryocooler. However, even for a pulse tube cryocooler, both the vibration level at the cold stage and the acceleration level at the cold head are still far from the requirement of the CLIO.

VIBRATION REDUCTION SYSTEM

In order to meet the low-vibration requirement, innovative methods were applied to a commercially available basic 4 K pulse tube cryocooler, SRP-052A, a product of Sumitomo Heavy industries, Ltd. The original cooling power of this cryocooler is 0.5 W at 4.2 K and 20 W at 45 K by using a 7 kW GM type compressor [4]. The cryocooler consists of a two-stage cold head, a rotary valve unit, flexible hoses of 20 m long for discharge and return gas and a helium compressor. A schematic diagram of the developed vibration-free pulse tube cryocooler system is shown in Figure 1.The main components of the system are a cold head mounted on a rigid frame, a split rotary valve unit on the table and a cryostat with an isolation bellows and the vibration-reduction (VR) stages with heat link.

Reduction of intrinsic displacement due to pressure oscillation

A couple of reports on the reduction of the cold stage by using flexible thermal links have already been published for specific applications with low-vibration requirements [5,6]. It has been reported that this method can reduce the vibration level down to ~1/10 of the original cold stage. We used braided wires of oxygen-free copper for the high-temperature 1st stage, and braided aluminum wires with high purity for the 2nd stage. The diameter of each thin wire is 0.1 mm. The Young's modulus of the aluminum wire is ~1/3 of that of the copper wire. Moreover, the spring constant becomes much smaller with keeping the same heat conduction by using the thinner wires. Two VR stages are supported by the alumina fiber FRP (AFRP) pipes from the cryostat lower flange.

Cold head supporting stage and rotary valve table

As shown in Figure 1, the support stage of four I-beam poles sustains the weight of the cold head and any kinds of vibration coming into the cold head will be short-cut to the ground. The VR stages are isolated from the cold head by a welding bellows. Since a driving motor for the rotary valve and the compressor generate a mechanical vibration, the rotary valve table is introduced to cut off the vibration. Flexible tubes from the compressor and rigid tubes to the rotary valve are all fixed by cramps. One of the features of the system is a connecting rigid tube of 40 cm long to separate the rotary valve from the cold head. Figure 2 shows pictures of the system and the details of the vibration-reduction stages.

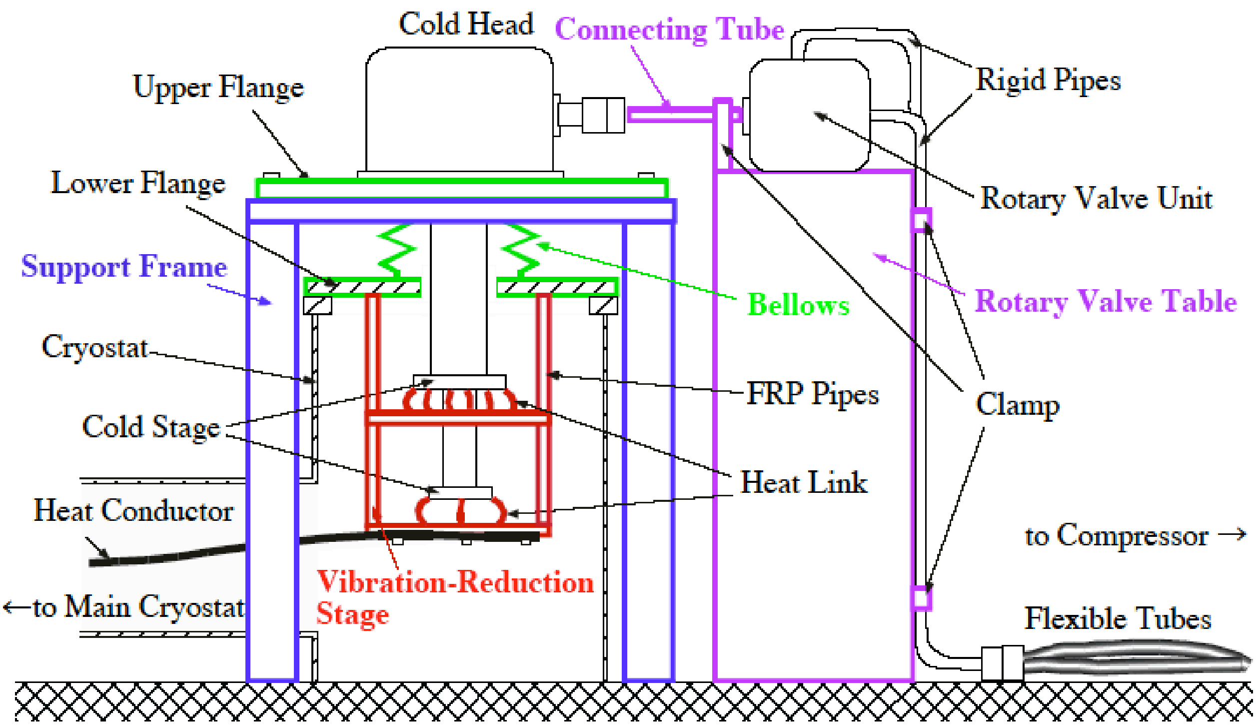

Figure 1. Schematic diagram of the vibration-reduction system for a 4K PT cryocooler. The compressor is not shown.

(a) (b)

Figure 2. Pictures of the vibration-reduction pulse tube cryocooler system. (a) Support frame and rotary valve unit on the table, (b) Heat link and the alumina FRP support rods.

PERFORMANCE OF THE SYSTEM

Cooling power with VR stages

In the CLIO system, a nominal cooling power of 15 W at 45 K and 0.4 W at 4.2 K is required. Table 1 summarizes the measured cooling power in various configurations. Due to a kind of thermal resistance at the contact surface of the heat link, the temperatures at each VR stage are 2-3 K for the 1st VR stage and 0.2-0.3 K for the 2nd VR stage higher than that of each cold stage [7].

Table 1. Comparison of the cooling power achieved in various configurations (by a 7 kW compressor).

Configuration	1st stage temperature	2nd stage temperature
(1) SRP-052A original	40.8 K @20 W	4.08 K @0.5 W
(2) 40 cm connecting tube	42.2 K @20 W	4.17 K @0.5 W
(3) With VR stage -Cold stage direct -Reduction stage	 41.2 K **43.7 K @15W**	 4.15 K **4.43 K @0.5 W**

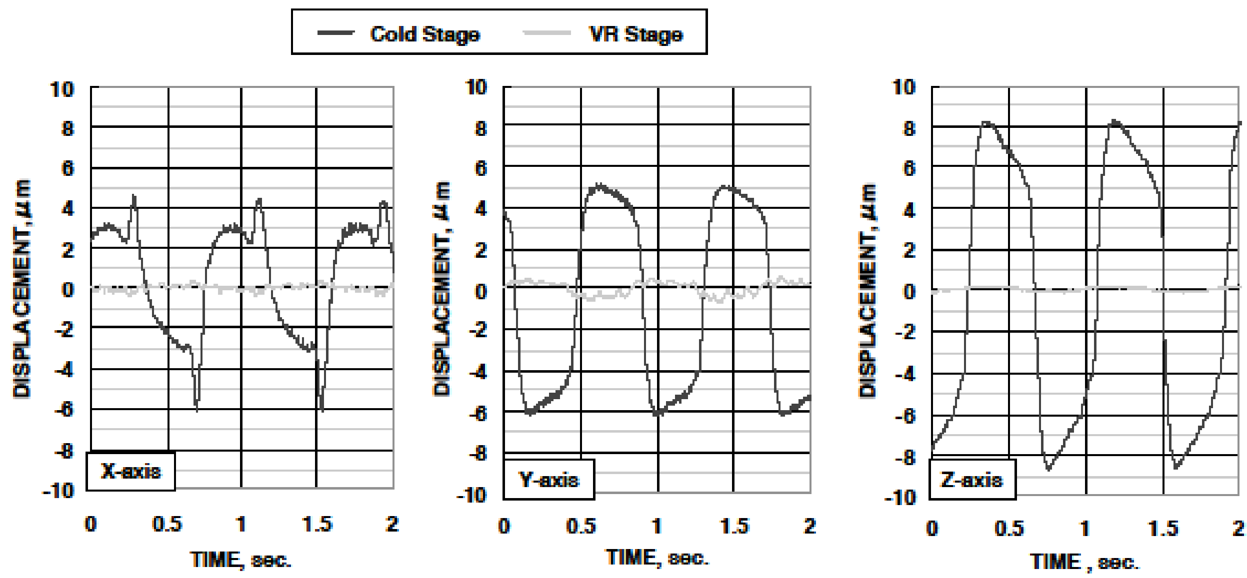

Figure 3. Measured typical vibration of the second VR stage and the cold stage.

Vibration at the VR stage

Figure 3 shows the measured vibration at the VR stage and the cold stage, which were measured by a laser displacement sensor (LC-2420, Keyence, Co., with a resolution of 10 nm). The vertical direction parallel to the pulse tube was defined as the Z-axis, and the direction of 15 degrees rotated from the central axis of the connecting tube was defined as the X-axis. The detailed vibrations in the X, Y and Z directions at the 2^{nd} cold stage and the VR stage are as follows: X-axis, +/-5.3 to +/-0.42 μm; Y-axis, +/-5.7 to +/-0.65 μm; Z-axis, +/-8.5 to +/- 0.05 μm. The effective vibration reduction is verified by using this method, especially in the Z-direction. The vibration at the 1^{st} stage is also evaluated the same in way as those of the 2^{nd} stage [7].

Overall vibration measurement in Kamioka mine

All of the system shown in Figure 1 was temporally installed in Kamioka mine for vibration measurements. It was confirmed that the vibration level of the lower flange of the system was identical to the seismic vibration level in Kamioka mine [8].

ON-GOING AND FURTHER PERFORMANCE TESTS

Before the final set of cryocoolers in the CLIO system, a set of 4 K and 80 K vibration-free cryocooler units was installed in the prototype cryostat for the final evaluation. The evaluation will be completed by this summer, and the following installation for the CLIO system will be started in Kamioka mine.

SUMMARY

A vibration-free 4 K pulse tube cryocooler system has been developed for the gravitational wave detector. The origin of two types of vibration in the cryocooler system was identified, and a vibration-reduction method has been developed. A thermal link by using bundles of thin pure aluminum wires was applied for vibration reduction at the cold stages, together with a bellows for vibration reduction at the cold head. The performance of vibration of 50 nm in the Z-direction at the second VR stage, and with a cooling power of 0.4 W at 4.2K and 15 W at 45 K has been achieved by using a 7 kW GM-type compressor. The overall vibration level was also confirmed as being identical with that of the seismic level at Kamioka mine. A vibration-free cryocooler system is now available for the gravitational wave detectors in the CLIO.

ACKNOWLEDGEMENTS

This research was supported by a Grant-in-Aid for Scientific Research on Priority Area (14047217) prepared by Ministry of Education, Culture, Sports, Science and Technology in Japan.

REFERENCES

1. Kuroda, K. et al., “Large-Scale Cryogenic Gravitational Wave Telescope”, Int. J. Mod. Phys. D, Vol. 8 (1999) p.557.
2. Ohashi, M. et al., “Design and Construction Status of CLIO”, *Class. Quantum Grav.*, Vol. 20 (2003) pp. S599-S607
3. Tomaru, T., Suzuki, T., Haruyama, T., Shintomi, T., Yamamoto, A., Koyama, T., Li, R. and Matsubara, Y., “Vibration Analysis of Cryocoolers”, *Cryogenics*, Vol. 44, (2004), pp.309-317.
4. Xu, M.Y., Yan, P.D., Koyama, T., Ogura, T. and Li, R., “Development of a 4 K Two-stage Pulse Tube Cryocooler”, *Cryocooler 12*, Kluwer Academic/Plenum Publishers, New York (2003), pp. 301-307.
5. Wang, C. and P.E. Gifford, “Performance Characteristics of a 4 K Pulse Tube in Current Applications”, *Cryocooler 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 205-212.
6. C. Lienerth, G. Thummers and C. Heiden, “Low-Noise Cooling of HT-SQUIDs by Means of a Pulse Tube Cooler with Additional Vibration Compensation”, *Proceedings of the 18th International Cryogenic Engineering Conference*, Narosa Publishing House, New Delhi (2000), pp. 555-558.
7. Li, R., Ikushima, Y., Koyama, T., Tomaru, T., Suzuki, T., Haruyama, T., Shintomi, and Yamamoto, “Vibration-free pulse tube Cryocooler system for Gravitational Wave Detectors II – Cooling Performance and Vibration –”, to be published in *Cryocooler 13*, Kluwer Academic/Plenum Publishers, New York (2005).
8. Tomaru, T., Suzuki, T., Haruyama, T., Shintomi, T., Sato, N., Yamamoto, A., Ikushima, Y., Li, R., Akutsu, T., Uchiyama, T. and Miyoki, S., “Vibration-free pulse tube Cryocooler system for Gravitational Wave Detectors I – Vibration-Reduction Method and Measurement –”, to be published in *Cryocooler 13*, Kluwer Academic/Plenum Publishers, New York (2005).