論文の内容の要旨

Study of a cryogenic suspension system for the gravitational wave telescope KAGRA
(重力波望遠鏡KAGRAのための
低温懸架システムの研究)

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Gravitational wave is a propagation ripple of space-time at the speed of light, predicted by Albert Einstein around a century ago. Since the gravitational wave has extremely weak interaction against material, the permeability is very high. This also means the gravitational wave should be a new observation window to the universe. Hulse and Taylor showed the existence of the gravitational wave indirectly by the observation of a binary pulsar. They received the Nobel Prize in 1993 for this discoverer. But the gravitational wave has not been observed directly until now.

Many groups in the world are developing gravitational wave telescopes to observe the gravitational wave directly. The most common type telescope for the gravitational wave is currently large Michelson interferometer. The Michelson interferometer measures the change of the distance between "free" masses (actually, suspended mirrors). Because the effect of the gravitational wave is extremely weak, many noises should be suppressed. For example, in order to suppress seismic vibration noise, multi suspension systems are used for the mirrors in the telescopes. Besides thermal noise because of the mirrors, coatings and suspension are also the fundamental noise sources.

KAGRA is the project to construct the first km-scale cryogenic interferometric gravitational wave detector (for thermal noise reduction) in the Kamioka mine, in short, underground site with small seismic motion. The main mirror of KAGRA will be held by a cryogenic suspension system (Fig.1) under a super seismic attenuation system. A study of this cryogenic suspension system which holds the cryogenic mirror is necessary for KAGRA. The cryogenic suspension system consists of a platform, an intermediate mass, a recoil mass of the intermediate mass, a recoil mass for the mirror and the sapphire suspension system (Fig.2) including the sapphire mirror. The cryogenic suspensions will be cooled down to ~20K using cryostats. Each cryostat consists of double radiation shields surrounding the cryogenic suspension system in a vacuum chamber. Four pulse tube cryocoolers for each cryostat will cool the shields and the cryogenic suspension. The mirror will be suspended by four sapphire fibers, which is called the sapphire suspension system. This system will be cooled by thermal radiation and thermal contact via the fibers and soft heat links between the suspension and the cryocoolers. There are two issues for this suspension system and cooling system, which are described in this thesis. One of them is the suspension thermal noise because of the sapphire suspension system. The other one is the vibration noise because of the cooling system via heat links.

The sapphire suspension consists of a mirror, two ears attached on the mirror, four fibers with heads suspending the mirror via the ears, and four blades to support the fibers. All of these components are made of sapphire. Moreover, strength bonding like Hydroxide Catalysis Bonding (HCB) and detachable bonding like indium bonding will be used between the mirror and the ear, and between the ear and fiber head, respectively. In designing this system, what we need to know are the mechanical loss, the heat conductivity and the strength of each part of the sapphire suspension system. These topics are the main parts of this thesis. The thermal noise depends on the mechanical loss of each part in the system. Low mechanical loss means low thermal noise. Because the mirror will absorb the main laser during the interferometer operation, the heat should be extracted through the sapphire suspension system. So the temperature of the mirror depends on the thermal resistance in the system. High thermal conductivity means low temperature mirror.

Mechanical loss measurements of fibers, HCB and indium bonding at low temperature are investigated. Three kinds of sapphire fiber were measured, then one of them had an extremely low mechanical loss 1.1×10^{-7} which is better than the required value 2×10^{-7}. The author and colleagues also measured the mechanical loss of indium bonding and HCB. We bonded two sapphire cylinders by each bonding technique and measured the mechanical dissipation of these sapphire cylinders. In the result the measured loss of the indium bonding was 3.1×10^{-3}, which is lower than the requirement value 1.5×10^{-2}. The measured HCB mechanical loss was below 1.0 at 20K, which is also below the requirement value 1.0. Therefore, all of the measured mechanical losses satisfied the requirements.

We also measured the heat extraction by the fiber, indium bonding and HCB. We measured thermal conductivity of sapphire fibers with nail heads and found that the values are between 5500 W/m/K and 6500 W/m/K and larger than the requirement, 5000W/m/K. We also measured the thermal resistance of the bonded sapphire samples to determine if the bonding had significant thermal resistance at low temperature. In the result we found the bondings will not influence the heat extraction from the mirror. So every component also satisfied the requirement in terms of the heat extraction.

Strength test of fibers had been done by our collaborators. According to the results, all of the fibers could hold at least 6 times heavier mass than the case of KAGRA. In our laboratory, we performed strength tests for the bonding technique, especially for HCB, which will hold the mirror mass. Since the cryogenic suspension is thought to experience 20 thermal cycles in 10 years at most, we did a strength test at liquid helium temperature after 10 and 20 thermal cycles for the bonded samples by HCB. Then all of the samples, including samples after 20 thermal cycles had higher strength than a required value 1MPa. Because the indium bonding surfaces are not designed to hold any masses, the strength test for this bonding is not necessary.

Therefore, all of the worrying components of the sapphire suspension system were studied and satisfied the requirements at last.

Another important issue is the vibration noise from the cooling system. In order to estimate the influence, we measured the vibration of the radiation shield of KAGRA cryostat for the design of cryogenic payload. The most practical way to reduce the vibration from the cryocoolers are fixing the cooling path on a massive structure like the radiation shield. If so, we can estimate the influence of the cooling system by measuring the vibration of the radiation shield during the cryocoolers operating.

Two cryogenic accelerometers were developed. (One of them is developed by collaborators at the Rome university.) A vibration measurement of the KAGRA cryostat was performed during its cooling test just after the manufacturing in a factory in an urban area. The vibration measurement of the outside cryostat was also performed using a commercial accelerometer at the same time in order to estimate the vibration of the cryostat in the Kamioka mine. Comparing the vibration during operation of the coolers to the vibration when the coolers had been turned off was also performed in order to estimate the influence of the cryocoolers. From these two measurements we estimated the vibration of the radiation shield at the Kamioka mine.

Then we calculated the displacement noise because of this radiation shield vibration through the heat links and the cryogenic suspension system assuming a suspension model. We found this displace noise can exceed the design sensitivity of KAGRA. Accordingly, we proposed an additional vibration attenuation system for the vibration of the cooling system. This system can suppress the displacement noise below the design sensitivity of KAGRA.

As a result, we are now quite confident that we can construct the cryogenic sapphire suspension using these components and techniques, and also the vibration due to the cooling systems will not make a significant noise.

For creating a new gravitational wave astronomy, large interferometer gravitational wave telescopes such as Advanced LIGO, Advanced VIRGO, GEO and KAGRA are under upgrade or being built currently. KAGRA will be the first km-scale cryogenic telescope using the cryogenic mirror suspension systems, which will be necessary for the future ground-based telescopes including the Einstein Telescope. The cryogenic type interferometers have the possibility to achieve much higher sensitivity, which can observe more gravitational wave events and discover new physics and astronomy. Therefore, the study in this thesis about the cryogenic suspension is a significant milestone for the future gravitational wave telescopes and also for a new gravitational wave astronomy.

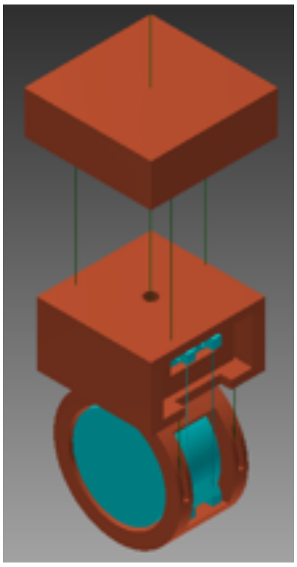

Figure 1. KAGRA cryogenic suspension system. The top box is called platform (PF). A box suspended from PF is the recoil mass (IR) of the intermediate mass (IM) which is suspended from the platform by a wire. A cryogenic sapphire suspension is suspended from IM. Finally a recoil mass (RM) of the mirror is suspended from IR.

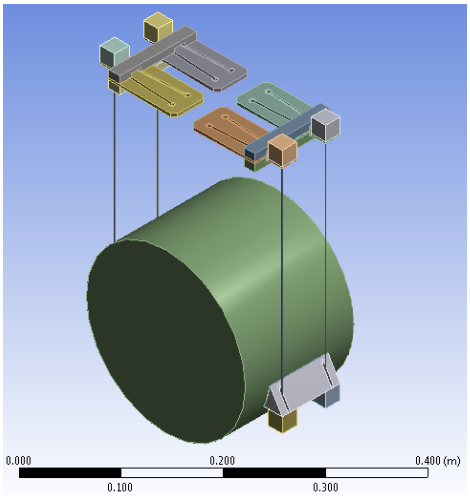

Figure 2. Cryogenic sapphire suspension system. There are two ears attached on the side of the main mirror. Four sapphire fibers with heads support the mirror via the ears. Sapphire blade is holding the fiber from the bottom the upper fiber head.