Cryogenic suspension design for a kilometer-scale gravitational-wave detector

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Abstract. We report the mirror suspension designs for Large-scale Cryogenic Gravitational wave Telescope, KAGRA. Mirror thermal noise is one of the fundamental noises for the room-temperature gravitational-wave detectors such as Advanced LIGO and Advanced Virgo. Thus, reduction of thermal noise is inevitable for further improvement of their sensitivity. One effective approach for reducing thermal noise is to cool the mirrors. However, there are many items to be considered for cooling the mirrors such as vibration induced from cryocoolers, suspension drift due to the thermal contraction, and deterioration of a duty cycle of an operation. Our mirror suspension has a black coating that prompts radiative cooling effectively. For conduction cooling, we developed ultra high purity aluminum heat conductors, which yields a high thermal conductivity while keeping the spring constant sufficiently small. A unique inclination adjustment system, called moving mass, is used for aligning the mirror orientation in pitch. Our suspensions have already been installed at the KAGRA site, and test operation called bKAGRA Phase 1 operation was performed. In bKAGRA Phase 1 operation, no fatal problem was found. The mirror temperature reached to 18 K, which is lower than the target temperature, 20 K. Initial mirror inclination adjustment at cryogenic temperature was achieved, and a 3-km Michelson interferometer was locked. Given the successful demonstration of these functionalities, our suspension design can serve as a standards of cryogenic mirror suspension for future kilometer-scale cryogenic gravitational-wave detectors, such as LIGO Voyager, Cosmic Explorer, and Einstein Telescope.

1. Introduction

In 2015, Advanced LIGO detected gravitational waves (GWs) from a binary black hole coalescence [1]. Since then, many black hole mergers and a neutron star binary coalescence were detected [2]. These GW observations enabled to test the general relativity under strong and dynamic gravity [3], estimate a rate of the compact binary coalescences [4, 5], reveal parameters of black holes [6], and measure the Hubble constant [7]. Thus, they opened an era of GW physics and astronomy. For their further promotion, it is significant to operate detectors at higher sensitivity than current detectors.

The ground-based GW detectors such as LIGO, Virgo, and KAGRA have to detect tiny displacement on the order of $10^{-19}$ m of the mirrors that are placed several kilometers apart from each other. In order to reach such a high sensitivity, it is inevitable to reduce displacement induced by the environmental effects as much as possible. Materials at a finite temperature cause motion called thermal noise, which is one of the dominant noise sources of the laser interferometric GW detectors [8, 9, 10]. It is therefore important to reduce thermal noise of the GW detectors.
KAGRA is an interferometric GW detector located in Japan. There are two unique features: KAGRA is constructed at underground site, where ground motion is smaller than the surface, and uses cryogenic sapphire mirrors as test masses to reduce thermal noise. Since thermal noise can be reduced by utilizing material with high mechanical quality factor (Q-factor) for the mirrors and their suspensions, KAGRA uses sapphire mirrors that has a high mechanical Q-factor close to $10^8$ at cryogenic temperatures [11] and cool it down to 20 K. However, there are several technical difficulties such as heat extraction from mirrors, reduction of vibration induced from cryocoolers, and mitigation of suspension drift due to thermal contraction.

The first cryogenic mirror suspension of KAGRA was installed on 30th of November, 2017. Subsequently, it was cooled down from February and achieved a temperature below 20 K in March, 2018. KAGRA then performed a test operation, named bKAGRA Phase 1 operation, in a simplified optical configuration from 28th of April to 7th of May, 2018 [12]. A part of characterization of the cryogenic mirror suspension was done during bKAGRA Phase 1. In this paper, we summarize our suspension design and its performance.

2. Mechanical design of a cryogenic payload

2.1. Overview

The KAGRA test masses (sapphire mirrors) are suspended by nine-stage vibration isolation system with 13.5 m in height named the Type-A suspension. The upper five stages, collectively called the Type-A tower, are at room temperature and the lower four stages, a cryogenic payload, are cooled down to 20 K. The four stages are platform (PF), marionette (MN), intermediate mass (IM), and test mass (TM) from the top. The TM chain, which consists of TM, IM, and MN, is surrounded by their corresponding recoil masses (RMs) to mount the displacement sensors and actuators [13]. TM is made of sapphire and RM is made of low-magnetism stainless steel so as not to induce unexpected magnetic force to the suspension. The other suspensions are made of stainless steel of SUS316L. Figure 1 shows drawings of the Type-A tower and the cryogenic payload.

PF is suspended from the bottom stage of the Type-A tower (Bottom filter, BF) by using a 3.3 m-long Maraging steel rod. A TM chain and corresponding RMs (RM chain) are suspended from PF individually. The TM chain is suspended by a single Maraging steel rod with three copper beryllium (CuBe) blade springs, four CuBe wires, and four sapphire fibers with four sapphire blade springs from the top. The RM chain is also suspended by three CuBe rods, four CuBe wires, and two looped CuBe wires from the top.

Since we utilize a geometric anti-spring (GAS) filter [14] for vertical vibration isolation in a room temperature suspension, the total weight of a cryogenic payload must be adjusted to their proper load, which is designed as 200 kg or slightly heavier. For the reason, the total weight of the cryogenic payload is designed as 198 kg to remain
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Figure 1. (Left) Appearance of Type-A tower. Type-A tower consists of five stage, F0, F1, F2, F3, and BF from the top. F0 is set on the inverted pendulum for low-frequency horizontal vibration isolation. Figure is adapted and revised from Ref.[12] (Right) Appearance of a cryogenic payload. Figure is also adapted and revised from Ref.[12].

Table 1. Summary of the mechanical design of each stage. Both test mass chain and recoil mass chain are suspended from platform (PF) separately. Test mass stage consists of marionette (MN), intermediate mass (IM), and test mass (TM) from the top. Recoil mass chain also consists of three stages: marionette recoil mass (MNR), intermediate recoil mass (IRM), and recoil mass (RM) from the top.

| Stage | Weight | Suspension wire | Number of wire | Wire length | Wire thickness |
|-------|--------|-----------------|----------------|-------------|----------------|
| PF    | 65 kg  | Maraging steel  | 1              | 3300 mm     | 12 mm          |
| MN    | 21 kg  | Maraging steel  | 1              | 345 mm      | 7 mm           |
| IM    | 19 kg  | Copper Beryllium| 4              | 241.3 mm    | 0.6 mm         |
| TM    | 23 kg  | Sapphire        | 4              | 350 mm      | 1.6 mm         |
| MNR   | 21 kg  | Copper Beryllium| 3              | 138 mm      | 7 mm           |
| IRM   | 20 kg  | Copper Beryllium| 4              | 242.7 mm    | 0.6 mm         |
| RM    | 29 kg  | Copper Beryllium| 2              | 243.5 mm    | 0.6 mm         |

a margin for some additional weights that can be mechanically attached on several stages. Table 1 is a summary of each stage of the cryogenic payload. Figure 2 shows a schematic view of configuration of the cryogenic payload.

There are three kinds of local sensors on a cryogenic payload for local control of suspensions. One is angular sensing optical levers (AS OpLevs) on MN and TM for sensing their angular motions [15]. Another is a length sensing optical lever (LS OpLev) on TM for sensing its motion along optical axis of a main interferometer [15]. The other is photo-reflective displacement sensors (PSs), which consists of one light-
emitting diode (LED) and two photo detectors (PDs), on marionette recoil mass (MNR) and intermediate recoil mass (IRM) for sensing relative displacement between a TM chain and an RM chain [16]. Although suspensions in LIGO and Virgo, which are operated at room temperature, use shadow sensors [17], it is difficult to apply them directly to a cryogenic suspension because thermal contraction of suspensions cause large misalignment and dynamic range of shadow sensors is too small in such condition. Therefore, we adopt photo-reflective displacement sensors, which have relatively larger dynamic ranges than shadow sensors.

There are two kinds of actuators on a cryogenic payload for the local and global control of suspensions. One is a coarse alignment control actuator called moving mass on PF and MN. Figure 2 shows a schematic view of the moving mass system. The moving mass changes a center of mass of PF and MN as it moves and controls the inclination of an RM chain and TM chain, respectively. The moving mass system consists of three components: a ball screw, copper block, and stepper motor. The ball screw is an oil-free type to be compatible with ultra-high vacuum and avoid to stack the screw at cryogenic
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temperature. The copper block is a simple rectangular box shape, which is 45 mm in length, 45 mm in width, and 40 mm in height, with a metal sphere that assists a smooth movement of the mass. The stepper motor is a cryogenic compatible model. The whole system is 202.5 mm in length, and actuation range and resolution of moving mass is $\pm 24.4 \text{ mm}$ and $1.25 \mu\text{m}$, respectively. The other is a coil-magnet actuator that is utilized for precise control of the suspension. MN, IM, and TM have magnets and their RMs have corresponding coils. We can provide force to the suspensions by applying current to the coils. All magnets are samarium-cobalt (SmCo), whose magnetism is not drastically changed even at cryogenic temperature [18]. Each coil makes a small module, PS module that consists of a PS and coil, to save space by combining sensors and actuators. Figure 2 shows a schematic view of a PS module. Detail of PS will be given in a separate paper [16].

2.2. Platform stage

PF suspends a TM chain and an RM chain separably for reducing vibration from cryocoolers transmitted to the TM chain. Since the heat conductor from cryocoolers are attached to MNR at first, the vibration to the TM chain is isolated by PF. Moreover, PF has a three CuBe blade springs, which have bounce mode with resonant frequency of 3.5 Hz, for mitigating vertical motion of the TM chain. The CuBe blade springs are installed with an angle of 7.5 degrees in order for their tips to be flat when the TM chain is suspended.

PF is also used for adjusting the inclination of an RM chain to a TM chain by utilizing moving masses. Although the internal diameter of coils, which is 15 mm, on the RM chain is much larger than that of magnets, it is important to set magnets at almost center of coils in order to avoid touching each other after cooling because of thermal contraction. In addition, since magnetic-field gradient is zero when magnets are at the center of coils, efficiency variation due to relative position change between the coil and magnet by thermal contraction can be minimized.

2.3. Marionette stage

An MN stage is used to adjust an inclination of TM to an injected beam, especially for pitch inclination. MN has two moving masses as well as PF for rough alignment of a TM chain. Figure 3 shows inclination changes of sapphire mirror by using the moving mass system on MN. From this result, we can calculate the actuation range as $\pm 11 \text{ mrad}$ and resolution as $0.6 \mu\text{rad}$. Since coil-magnet actuator on MN stage can actuate mirror angle by more than $10 \mu\text{rad}$, the resolution of $0.6 \mu\text{rad}$ is small enough to operate KAGRA interferometer. Also actuation range is much larger than the drift of pitch inclination during cooling, which was about $100 \mu\text{rad}$ during bKAGRA Phase 1 [12].

Another role of the MN stage is to damp yaw motion of the TM chain. Since the TM chain is suspended by a single wire from PF, yaw motion of MN is easy to be excited and disturbs an interferometer operation. On the other hand, an RM chain is
suspended by three rods and its yaw motion is rigid compared to that of the TM chain. So, we can damp yaw motion of TM chain by using the relative displacement signal of PSs. The yaw motion of cryopayload, which is suspended by maraging steel wire with 3.3 m in length between BF and PF is also damped at MN because PF does not have any actuator and sensors. Although this motion cannot be seen by PSs, we can use OpLev signal to damp.

The other role of MN is to control longitudinal motion at low frequency region during operation of the interferometer. To reduce noise from actuation, IM and TM stages have relatively small magnets compared to those of MN. So, longitudinal motion control at low frequency is implemented by using MN-stage actuators.

2.4. Intermediate mass stage

Most significant role of an IM stage is to suspend sapphire mirrors so as to reduce suspension thermal noise as much as possible. Thus, sapphire fibers, which has high Q-factor at low temperature, are used for mirror suspension. However, uniformity of sapphire fibers’ length is about 1 mm in fabrication process though elastic stretch of sapphire fiber with the loading of mirror weight is only dozens $\mu$ m. It is thus difficult to absorb fabrication errors by elastic deformation of the fibers. Therefore, sapphire blade spring is installed on IM to mitigate length difference between each fiber.

A sapphire blade spring has M-shape for obtaining low resonant frequency of bounce mode in a small space. The thickness of the blade is tapered to be strong enough to support the TM load. The sapphire blade springs are set on IM inclining an angles of

Figure 3. Result of moving mass performance test. Change of angle is measured by an optical lever. Red dots and black line are measured values and fitting line, respectively. The slope of fitting line is about $0.5 \text{ rad/m}$. 
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Figure 4. (Top left) Schematic view of a sapphire blade spring. A slit for hooking a sapphire fiber is L-shape in order to avoid slipping the fiber. Sapphire blades have a taper to be compact and strong enough to suspend mirror. Thinner side, L-shape slit part, is 2 mm and thicker part, the opposite side of thinner side, is 4.5 mm. (Top right) Schematic view of a sapphire ear. Ear shape is triangular prism with 80 mm in height. There are two slits 60 mm apart from each other for hooking the sapphire fibers. (Bottom) Schematic view of a sapphire fiber. There are 20 mm × 20 mm × 10 mm rectangular blocks at both edges. The length and diameter between both blocks are 350 mm and 1.6 mm, respectively.

1.9 degrees as well as a CuBe blade spring on PF. A schematic view of the sapphire blade spring is shown in Fig. 4.

The other role of the IM stage is to damp eigenmodes of suspension that cannot be damped at an MN stage. There are several eigenmodes that cannot be monitored at the MN stage. Therefore, IM stage is also used for damping control of the cryogenic payload.

2.5. Test mass stage

TM is the most important part of the cryogenic payload for achieving design sensitivity of KAGRA [19]. TM is made of monocrystalline sapphire that has high mechanical Q-factor, high thermal conductivity [20], and low absorption rate for 1064 nm light like 50 ppm/cm [21]. TM also has high reflective or anti-reflective multi-layer coatings for the 1064 nm laser, and their optical absorption rate is small enough in order of sub ppm [22].

To suspend mirrors, we use sapphire fibers with nail heads and sapphire ears with slits. Figure 4 shows a schematic view of a sapphire ear and sapphire fiber. A sapphire fiber has two rectangular blocks at both edge to hook themselves to the sapphire ear and sapphire blade spring. The blocks are bonded by inorganic adhesive called SUMICERAM. The sapphire ear is triangular prism with 80 mm in height. The ear has two slits apart from 60 mm each other to hook the sapphire fibers. Sapphire ears are bonded at the side of a sapphire mirror and suspended from sapphire blade spring on IM as shown in Fig. 5.

Bonding between a mirror and ear should be strong enough to support mirror
weight at cryogenic temperature. In addition, mechanical loss of bonding must be small enough not to increase thermal noise. Since hydroxide catalysis bonding (HCB) method [23] satisfies both high strength and low mechanical losses [24, 25, 26], HCB is used for the bonding between the mirror and ears. Sapphire ears are attached at the position of 47.8 mm lower than the center of mass of a mirror because a bending point of fibers and the center of mass of the mirror should be on the same horizontal plane for reducing coupling between longitudinal and pitch motion.

Bonding between ears and nail heads are also necessary so as not to slip the fibers from the ears and to have sufficient thermal contact. Moreover, it must be possible to replace fibers in case of fiber breaking or other accidents. We thus use Ga bonding for their welding. Since the melting point of Ga is around 30°C, it is easy to melt Ga when we apply some heats. Ga is applied to the nail head and ear by using ultrasonic soldering iron in order not to peel off. This bond is also used between the other nail head and sapphire blade spring. Figure 5 shows a sapphire suspension system used in KAGRA.
3. Thermal design of a cryogenic payload

3.1. Overview

A cryogenic payload is cooled by thermal radiation and heat conduction in high and low temperature region, respectively. For effective radiation cooling, the cryogenic payload is coated by black plating called solblack coating that has a high emissivity. Soft heat conductors are connected between the cryogenic payload and two cryocoolers to decrease vibration induced from cryocoolers to TM.

There are two layers of radiation shields around a cryogenic payload for reducing thermal radiation from room temperature environment. Both radiation shields have multi-layers insulation made of polyimide films with evaporated aluminum for reducing the heat load by thermal radiation. Inner part of the radiation shields are coated by diamond like carbon coating to make effective heat extraction via thermal radiation. Cryogenic baffles are also installed in the beam duct of main interferometer to reduce thermal radiation.

Heat conductors for cooling in low temperature region are made of pure aluminum, which has a purity of over 99.9998% [27]. This ultra pure aluminum heat conductor has high thermal conductivity to cool the cryogenic payload effectively and flexibility to reduce the vibration through itself. In addition, heat link vibration isolation system (HLVIS) was installed after bKAGRA Phase 1 for further reduction of vibration via heatlinks. Detail of HLVIS will be given in a separate paper [28].

A cryogenic payload is cooled to 20 K by two double-stage pulse-tube cryocoolers (PTCs) that create very small vibration [29, 30]. Inner radiation shield is also cooled at 8 K by other two PTCs. Outer radiation shield is cooled by the first-stage of all four PTCs that are used for cooling of the cryogenic payload and inner radiation shield.

At beam ducts of both HR side and AR side, cryogenic duct-shields with 5 m in length are installed to reduce heat load of thermal radiation from room-temperature beam duct. They also have solblack coating to obtain effective reduction of thermal radiation and are cooled to 120 K by a single-stage PTC. Thanks to these cryogenic duct shields, the thermal radiation can be reduced by a factor of 100 and becomes 0.1 W per each beam duct [31].

3.2. Cryogenic payload

KAGRA mirror obtains heat of about 0.7 W by absorbing the main laser of an interferometer during the operation even though mirror substrate and coatings have very low absorption rate of 1064 nm laser. In order to extract such large heat without any large mechanical losses, sapphire fibers, which has a Q-factor of the order of 10^7, of diameter of 1.6 mm with nail heads are used for suspension. HCB and Ga bonding are also essential for reducing the thermal resistance of the sapphire suspension.

The heat is transmitted in order of IM, MN, PF, and MNR after transferring through the sapphire suspension. RM are also cooled and the heat is transmitted in
Figure 6. (Left) Schematic view of the KAGRA cryogenic system seen from the side. Heat extraction from sapphire mirror is through 4 sapphire fibers, and the other part of payload is cooled by using pure-aluminum heatlinks. MNR is connected to cooling bars, which is directly contacted to the second stage of 4K cryocooler, by the same heatlinks. Cryogenic duct-shield, which is cooled to 120K by single-stage cryocooler, is located at the both sides of cryostat along the beam tube. (Right) Schematic view seen from the top side. outer radiation shield is cooled by 4 first stage of two-stage PTCs, while inner shield is cooled by 2 second stage of them.

order of IRM and MNR through aluminum heatlinks. MNR is linked to cooling bars that are directly cooled by the cryocoolers. A schematic diagram of the cooling system is shown in Fig. 6.

The first KAGRA cryogenic payload was installed at the end of November, 2017 and started to be cooled down from the beginning of February, 2018. There were thermometers on the inner and outer radiation shields, cooling bars, and each stage of the payload: TM, RM, IM, IRM, MN, MNR, and PF. Thermometers are non-calibrated silicon diode thermometers, which have an error of 0.5 K in maximum.

Figure 7 shows the temperature of the suspension during the cooling. Unfortunately, we couldn’t measure temperature of MNR because its thermometer didn’t work well at that time. It spent almost one month to reach the steady state and mirror temperature was about 18K. This is almost consistent with our estimation of cooling time and it is acceptable for KAGRA operation. From 27th day to 29th day, temperature change of the payload was stopped because temperature balances fell into the metastable state. Thus, we once stopped cryocoolers on 29th day and restarted on 30th day. Then, the mirror temperature reached steady state at 34 days.

4. Discussion and Conclusion

We operated a 3-km cryogenic interferometer with our first cryogenic payloads and identified several issues during the operation. One was that the electrical cables running between BF and PF through a narrow cylindrical radiation aperture were found to be rubbing against the aperture, introducing large amount of vibration to TM. The issue
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Figure 7. Cooling curve during bKAGRA Phase 1. Figure is adopted and revised from Ref. [12]. Red curve, showing sapphire mirror temperature, reaches below 20 K within one month. Black line shows the temperature of BF, which is the nearest stage from the cryogenic payload. Even though the temperature of cryogenic payloads goes down, BF can be kept at room temperature because of the well-thermally-isolated system.

was resolved by tying the cables to the suspension rod without modifying the cylindrical aperture such that it preserves the ability of shielding the radiative heat input from BF and upper parts. Detailed is reported in Ref. [12]. The other was an issue with the moving masses being stuck. The moving mass can work at cryogenic temperature and has a good performance during the initial alignment. However, the long-term reliability is not excellent. Therefore, a new moving mass system was designed to solve this problem. Pulley and thin wire is used for driving a copper mass instead of a ball screw in the new design. A prototype test is currently underway.

Several good experiences are also obtained from the bKAGRA Phase 1 operation. The cooling time is almost same as what we expected and the mirror temperature reached below 20 K. In addition to this, the sensors and actuators worked properly at the cryogenic temperature. The payloads can be controled and the mirror motion can be reduced to a sufficient level where we can operate the 3-km interferometer. Thus, our first design of the cryogenic payload is able to provide stable platform necessary to operate the kilometer-scale gravitational-wave detector at the cryogenic temperature.

We designed and demonstrated the first cryogenic suspension for a km-scale interferometric gravitational-wave detector. A 23 kg sapphire mirror was suspended by four sapphire fibers of 1.6 mm in diameter and cooled below 20 K by conduction cooling via pure aluminum heatlinks. The sensors and actuators work well at the cryogenic temperature and show the sufficient performances for the operation of 3-km interferometer. No fatal issues were found and several issues we found in the first
cryogenic payload are almost successfully resolved. We also survey several upgrade based on our first design of the cryogenic payload [32]. This demonstration paves the way to LIGO Voyager, Cosmic Explorer, and Einstein Telescope [33, 34].

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