PROCEEDINGS OF SCIENCE

Control noise reduction of cryogenic suspension in KAGRA

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In gravitational wave detectors, the laser is used to observe how the distance between mirrors changes due to space distortions caused by gravitational waves. The displacement of the mirrors is minute, so the mirrors must be sufficiently isolated from ground vibrations to achieve the required sensitivity. Therefore, the main mirrors are suspended by nine-stage pendulums in KAGRA, the gravitational wave detector in Japan. In such a pendulum-based vibration isolator, the mirror oscillates significantly at the resonant frequency. Hence we need the control system to damp the resonances, but the noise from the sensors used in such a control system can be a problem. In fact, the sensitivity of KAGRA was limited by the noise from the cryogenic payload control system at 10-50 Hz in the previous observation. Therefore, a low-noise control filter was designed and implemented for use during the previous observing run. As a result, the control noise of the cryogenic payload at 10-100 Hz was reduced by 2-3 orders of magnitude, and the target sensitivity for the O4 observing run was achieved at low frequency (below 100 Hz).

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1. Introduction

Gravitational waves are space-time ripples derived from general relativity, and their existence was predicted by Albert Einstein in 1916 [1]. In 2015, gravitational waves from black hole binary mergers were directly detected for the first time by the Advanced LIGO detectors [2], finally proving their existence. In August 2017, the Advanced Virgo detector has joined the observations, and many gravitational waves from compact binary mergers have been detected [3]. In recent years, follow-up observations with gamma rays, X-rays, and neutrinos, together with gravitational wave information, have provided many new insights into the origin of heavy elements and the formation mechanism of gamma-ray bursts, information that was not available before. The multi-messenger observation, which aims at solving mysteries through the cooperation of observatories with different observing means, is developing, and there are high expectations for the gravitational wave observation to serve as a starting point for such observations [4]. Under these circumstances, the gravitational wave detector in Japan KAGRA started observations with LIGO (O4 observing run) in May 2023.

Laser interferometric gravitational wave detectors such as LIGO, Virgo, and KAGRA use lasers to observe minute changes in mirror spacing due to spatial distortions caused by gravitational waves. Because the displacement of the mirrors is minute, it is necessary to suppress the effect of ground vibration in order to achieve high sensitivity. Therefore, the ground vibration transmitted to the mirror at frequencies higher than the resonant frequency is reduced by suspending the mirror with a multi-stage pendulum-type suspension system. In addition, the mirror is cooled down to 20 K in KAGRA for the reduction of thermal noise [5]. The suspension for it is called cryogenic payload.

On the other hand, the ground vibration transmitted to the mirror is amplified at the resonant frequency of the pendulum, so it is necessary to control the pendulum to damp the resonances. However, the more the resonances are damped, the more the electrical noise from the sensor used for control (control noise) limits the sensitivity at low frequency [6]. Therefore, we needed to improve the control to reduce the control noise and achieve the target sensitivity in the O4 observing run. This paper begins with a brief introduction of KAGRA and the cryogenic payload, then describes the damping control and control noise. We then present our efforts to reduce the control noise and the results.

2. Cryogenic Payload in KAGRA

2.1 Main Suspension System in KAGRA

KAGRA is a laser interferometric gravitational wave detector with a baseline length of 3 km located in Kamioka-cho, Hida City, Gifu Prefecture, Japan. KAGRA has sapphire mirrors which are cooled down to 20 K to reduce thermal noise and is operated in an underground environment to reduce the influence of ground vibrations [7]. To further reduce the effects of ground vibration, we use a multi-stage pendulum-type suspension system, which can reduce the vibration transmitted to the mirror.

Depending on the application, KAGRA uses three different types of suspensions. The largest suspension, which is called the Type-A suspension, is used for the main sapphire mirrors and consists of nine stages, with a total height of 13.5 meters (Figure 1). KAGRA has four Type-A suspensions as shown in the figure. The top five stages of the Type-A suspension are called Type-A tower which is at room temperature, while the bottom four stages are called cryogenic payload which is cooled in the cryostat.

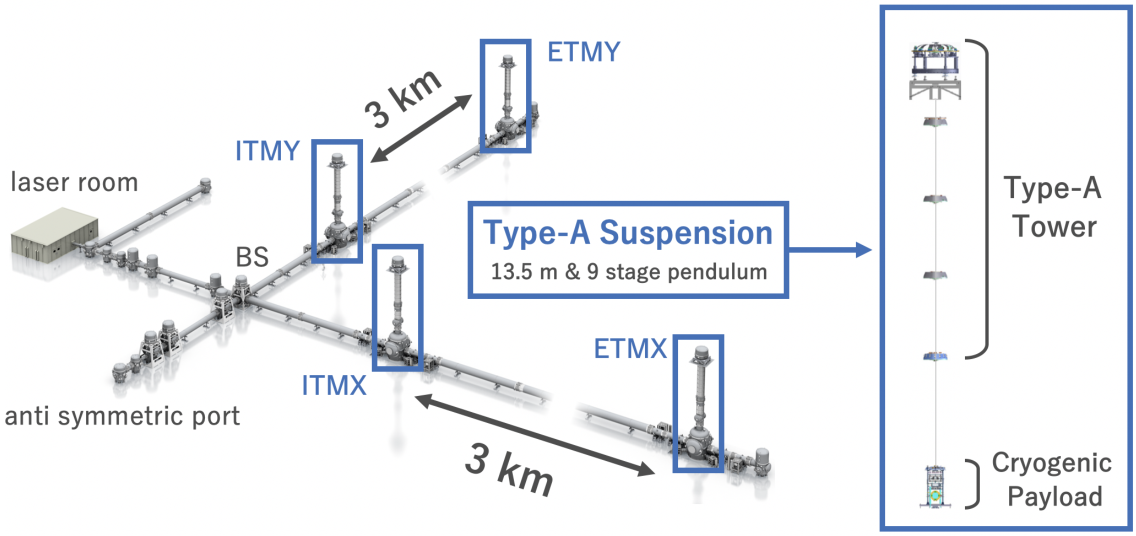

Figure 1: Type-A suspension in KAGRA. CG illustration of KAGRA layout is by Rey Hori.

2.2 Cryogenic Payload

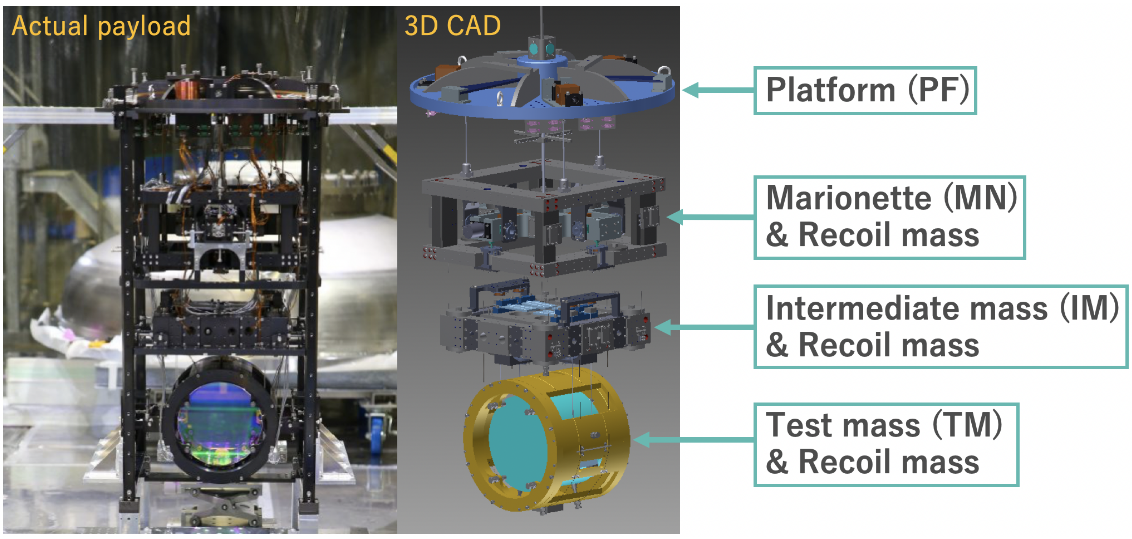

Figure 2: Crygenic payload in KAGRA. The photo of actual payload is taken by Rohan Mehra.

Cryogenic payload in KAGRA is a four-stage pendulum structure with platform (PF), marionette (MN), intermediate mass (IM), and test mass (TM) from the top (Figure 2). In addition, the MN, IM, and TM are equipped with a recoil masses which can provide an actuation force that is isolated from ground disturbances [8].

As for the sensors on cryogenic payload, the MN and the IM are equipped with photo-reflective displacement sensors to monitor the relative displacement between the mass and the recoil mass for each degree of freedom [8]. Furthermore, angular sensing optical levers are installed on the PF, the MN, and the TM to monitor the angular motion of the masses relative to the ground. In addition, they are also equipped with a length sensing optical lever to sense the motion along optical axis of the interferometer [9].

The displacement signal captured by these sensors is passed through a digital filter to the actuators [10]. The actuator applies the force to the mass to realize damping control, which is discussed in the next section.

3. Damping Control and Control Noise

3.1 Damping Control for Suspension System

In the case of a multi-stage pendulum vibration isolation system, a high vibration isolation ratio can be achieved at frequencies above the resonant frequency (left of Figure 3). On the other hand, the vibration transmitted to the mirror is amplified at the resonant frequency. In this case, the interferometer cannot maintain a stable state and the observation cannot be performed. Therefore, a damping control that damps the vibration at the resonant frequency is required.

Damping control is a feedback control in which the displacement of the mirror is locally detected by a sensor, and a force to cancel it is applied to the mirror by an actuator (right of Figure 3). In other words, when a certain force (disturbance) is applied to the suspension system, a sensor detects the response of the suspension system and sends a signal to the digital system. In the digital system, the signal is sent to the actuator through a filter to cancel the effect of the disturbance.

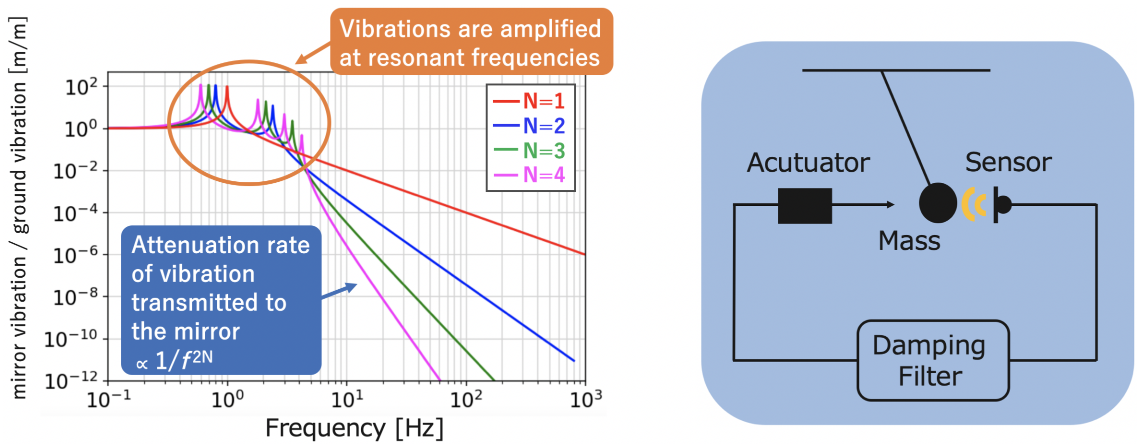

Figure 3: (Left) Vibration amplification at resonant frequencies and vibration attenuation rates at frequencies above the resonant frequencies. (Right) Schematic view of damping control.

To damp the resonant peak, we can design a high-pass filter i.e. a filter that differentiates the signal received from the photosensor in a certain region of the resonant frequency. On the other hand, at high frequencies above the control band, the gain is reduced by a low-pass filter to suppress the effect of noise. Furthermore, we should be careful to provide sufficient phase margin at the frequency where the gain of the open loop transfer function is 1 (Unity Gain Frequency, UGF).

3.2 Control Noise

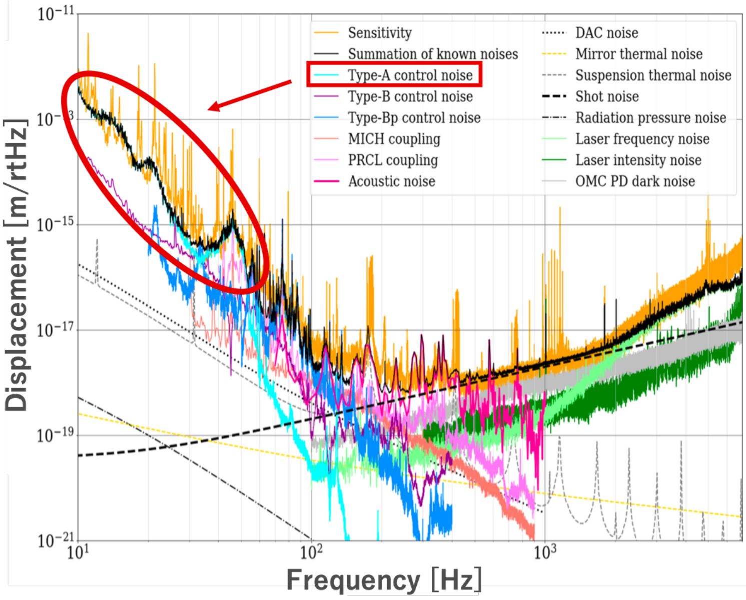

Figure 4: Control noise during previous observation [6].

Although a low-pass filter is applied at high frequencies, sensor noise is still a problem in feedback control. In addition, a suppression of vibration and a reduction of noise cannot be achieved simultaneously. In other words, the more we try to suppress the vibration, the more the noise is introduced, or vice versa, which is a major problem.

In fact, in the previous observation (O3GK), there was a problem that the noise from the control system of the cryogenic payload limited the sensitivity around 10 to 50 Hz [6]. The Figure 4 shows this, where the black line representing the sum of all noise and the light blue line representing the control noise of the cryogenic payload completely overlaps at 10 to 50 Hz. This means that the control noise of the cryogenic payload limited the sensitivity in this frequency band.

4. Control Noise Reduction

We introduced a new method of switching the controls depending on the state of the interferometer, thereby reducing the noise during the observation.

An interferometer is not ready for observation immediately after assembly. In the observation-ready stage, we want to control the position and angular of the mirror to quickly create an observable state, so we use a control that emphasizes vibration suppression, even if the noise may be a little louder. In the previous experiment, the observation was performed under this control, resulting in a large control noise as described above. However, in the observation stage, it is important to keep the stability and noise level low. Therefore, we designed a control filter (hereinafter referred to as "OBS filter") that reduces the effect of noise while keeping the minimum requirement for vibration suppression, and switched to this control during the observation phase.

As an example of an observation filter, we present the control of the pitch direction of ITMX (Figure 5). Note that pitch is one of the six degrees of freedom of the rigid body, and is the direction in which the mirror bends. The main modification is to apply an elliptic low pass filter with phase margin more than 20° at the unity gain frequency to reduce the gain at frequencies with higher gain in the observable-ready stage. This type of control modification has also been applied to other cryogenic suspension systems.

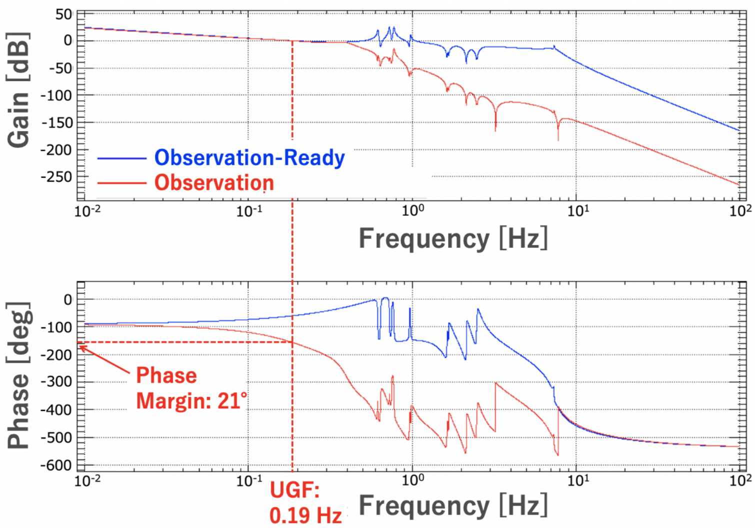

Figure 5: Changes in open loop transfer function due to control update (ITMX Pitch). Blue line shows observation-ready stage, and red line shows observation stage.

The control noise measurements were performed using the FPMI configuration. Here, FPMI is a Michelson interferometer with a Fabry-Perot cavity in its arm, and its schematic diagram is shown in Figure 6. In this FPMI, the gravitational wave signal is a differential signal in the arm, called the DARM signal, and is obtained from the photo detector shown in the Figure 6. A feedback signal is then fed back to the ETMX to drive the ETMX to maintain the differential displacement of the arms. To measure the control noise in the FPMI configuration, we then intentionally oscillated each suspension in each degree of freedom and measured the transfer function from that motion to the DARM signal. This transfer function was measured by intentionally shaking the suspension, but the noise from the sensors used for control is always present even when the suspension is not shaken in this way. By multiplying the amplitude spectral density of the sensor output without shaking by the transfer function obtained earlier, the control noise can be plotted on the sensitivity curve. Moreover, the total control noise can be calculated by summing squares for each suspension since the control noise of each suspension is uncorrelated.

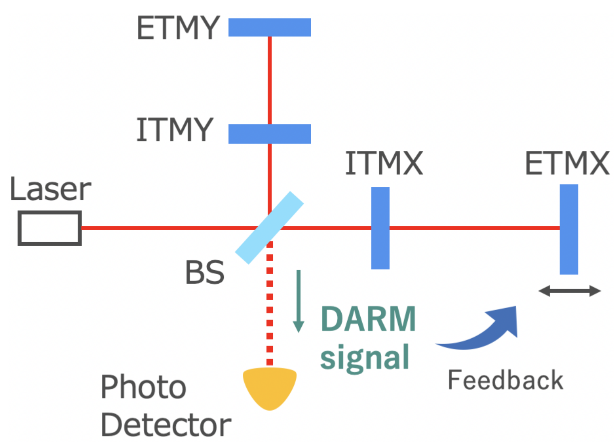

Figure 6: Schematic view of FPMI.

Figure 7 shows the result of control noise measurement. The control noise line changed from green to orange, and this means control modification successfully reduced the control noise by 2 ∼ 3 orders of magnitude. Moreover, this allowed us to achieve the target sensitivity of 10 Mpc for the O4 observing run. In addition, we were able to verify that the interferometer operated stably for at least more than 1 day. The operation test was terminated due to interferometric work before the observation, but without that, the interferometer would have remained stable for a much longer time. In any case, the new control was stable enough.

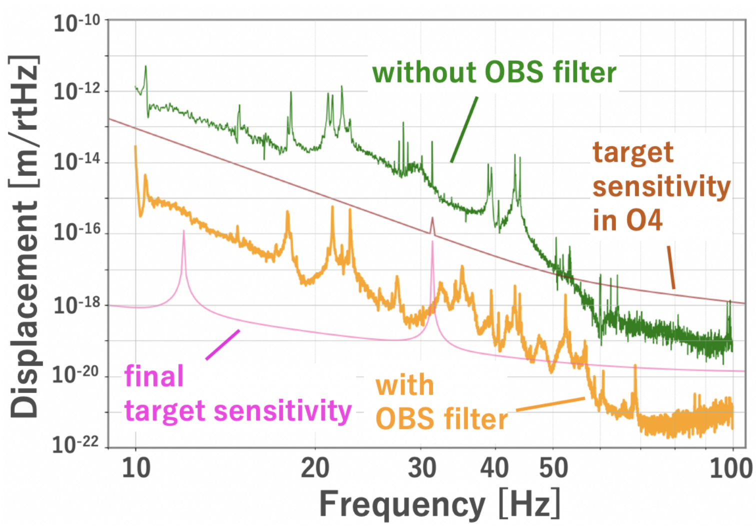

Figure 7: Control noise reduction by OBS filter.

5. Summary and Outlook

In summary, the newly designed control system has successfully reduced the control noise in the cryogenic payload by 2 ∼ 3 orders of magnitude while maintaining stable interferometer operation. This also enabled KAGRA to achieve its target sensitivity at low frequencies for the O4 observing run. However, as shown in Figure 7, we need to further reduce the control noise by $2 \sim 3$ orders of magnitude to achieve the target sensitivity for the next observation.

Therefore, as a future prospect, we would like to achieve the final target sensitivity of KAGRA at low frequencies by reducing the control noise. To achieve this, we should develop the new control system. In the current control system, the control parameters are determined by empirical design and adjusted by human hands. However, it should be possible to build an optimal control system based on numerical simulation. For example, a possible approach would be to decompose the pendulum vibration into modes based on a numerical model and then perform feedback control according to the shape of the vibration modes. This method is suitable for KAGRA suspensions, which are multi-degree-of-freedom oscillating systems and should be able to optimize the trade-off between control performance and noise more efficiently. In this case, it may be effective to introduce the H_∞ method to provide a robust control at the same time even when there are errors between the model and actual measurements. In addition, the sensors used for the control will need to be developed with higher performance, so we should work on that as well.

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