Active damping performance of the KAGRA seismic attenuation system prototype

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Abstract. The Large-scale Cryogenic Gravitational wave Telescope (formerly LCGT now KAGRA) is presently under construction in Japan. This May we assembled a prototype of the seismic attenuation system (SAS) for the beam splitter and the signal recycling mirrors of KAGRA, which we call Type-B SAS, and evaluated its performance at NAOJ (Mitaka, Toyko). We investigated its frequency response, active damping performance, vibration isolation performance and long-term stability both in and out of vacuum. From the frequency response test and the active damping performance test, we confirmed that the SAS worked as we designed and that all mechanical resonances which could disturb lock acquisition and observation are damped within 1 minute, which is required for KAGRA, by the active controls.

1. Introduction

KAGRA is a large cryogenic laser interferometric gravitational wave (GW) detector which is being constructed underground at the Kamioka mine in Gifu Prefecture Japan [1]. To avoid the GW signals from being buried in seismic noise, the mirrors of the interferometer are suspended by multi-stage pendulums called the seismic attenuation system (SAS), to prevent seismic motion from transferring to the mirrors and to let the mirrors move as free test masses. By suspending the mirrors, we can attenuate the seismic noise at frequencies higher than the resonance frequency of the SAS. However, the test mass would vibrate with large amplitudes at its mechanical resonance frequencies, so in order to lock the interferometer, we have to damp these resonances.

In KAGRA, we use three types of SAS for different tasks: Types A, B and Bp. The Type A SAS is an 8-stage pendulum system for the test masses (in the final full configuration which will be used for observation). For the beam splitter and signal recycling mirrors, we will use a 5-stage pendulum system called Type B SAS. The Type Bp SAS is a 3-stage pendulum system for the power recycling mirrors. In this paper, we report the Type B prototype test. In section

2, we summarize the design of the Type B SAS and its control strategy, and in section 3 the results are described.
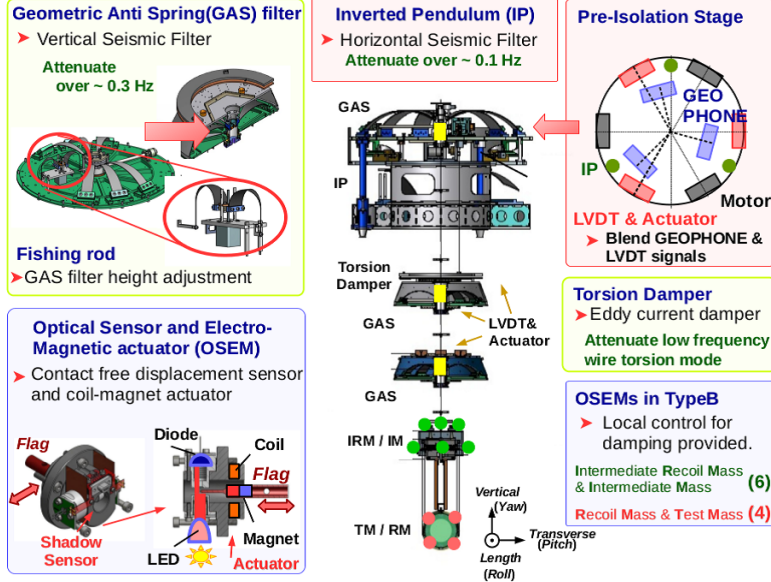

Figure 1. Overview of the Type B SAS for the beam splitter and signal recycling mirrors. The yellow boxes in the center show the position of the LVDTs and the actuators, while the red and green dots show the position of the OSEMs. We can actuate the top stage in 3 DoF, each GAS filter in the vertical direction, the IM for all 6 DoF, and the TM in 3 DoF.

2. Type B SAS

2.1. Mechanical details

The mechanical components of the Type B SAS are as follows (see also Figure 1);

- Inverted Pendulum (IP): three inverted pendulum legs support the whole system, and work as a horizontal seismic filter whose resonance frequency can be tuned as low as 0.1 Hz. The IP can attenuate not only the micro seismic noise at around 0.2 Hz, but also damp the multi-stage pendulum resonances around 1 Hz.

- Geometric Anti-Spring (GAS) filters: each filter is a vertical seismic isolator whose resonance frequency is tuned around 0.3 Hz. Type B SAS has three GAS filters. Each GAS filter consists of a set of curved maraging steel blades. It also has a spring height adjustment, in order to compensate thermal drift, attained through a motorised blade with low stiffness set in parallel to the GAS springs, called a fishing rod. The fishing rod can compensate weight of a few hundred grams.

- Torsion Damper: a non-contacting damper is placed above the middle GAS filter, which aims for damping low-frequency wire torsion modes of the SAS using eddy current damping.

- Payload: a 2-stage, 4-mass pendulum, which consists of the intermediate recoil mass (IRM), intermediate mass (IM), recoil mass (RM) and test mass (TM). We can adjust tilt and longitudinal displacement of the TM and the RM by applying forces on the TM from the RM.

Each component has sensors and actuators: The IP has three sets of coil-magnet actuators and two kinds of sensors arranged in a pinwheel configuration. Linear variable differential transformers (LVDTs) are used at low frequencies and geophones are used at high frequencies, with a crossover around 50 mHz. Each GAS filter has an LVDT as a vertical displacement sensor and a coil-magnet actuator. The payload is equipped with Optical Sensors and Electro-Magnetic actuators (OSEMs) [2] (see Figure 1), which combine shadow sensors and coil-magnet actuators. The linear range of the OSEMs is around 1 mm. By using 6 OSEMs on the IM and IRM, and 4 OSEMs on RM and TM, we can sense and actuate the relative motion of the IRM and IM in 6

DoF, and the RM and TM in 3 DoF. The signals from those sensors are to damp the resonances. An optical lever is also set at the front side of the TM to align the TM angular displacement.

2.2. Local active control strategy

Active damping controls are required to suppress the motion caused by the external disturbance driving the mechanical resonances of the SAS. The control system is set up to progress through the following states of operation: (a) damping, (b) lock acquisition and (c) observation [2]. The purpose of the damping state is purely to reduce large-amplitude motion at the mechanical resonances due to external disturbances. In this state the active controls are required to minimize the decay time of the SAS to allow fast recovery to the observation state. We have set a goal for the required damping time of 1 min. In the lock acquisition state the speed of the mirrors has to be suppressed to allow the mirrors to be trapped into the linear range of the interferometer signals. The control noise must be designed not to increase the RMS of linear speed of each suspended mirror. To lock the optical cavities, the RMS velocities and the angular fluctuations of the mirrors are typically required to be less than 1 μm/sec and 1 μrad respectively [3]. After lock acquisition is achieved, we enter the observation state, in which the interferometer operates. In each state, we use different control system, for example, OSEMs are used only in the damping and lock acquisition states because of their large noise coupling. Conversely, geophones are used in the lock acquisition ans observation state due to their small range.

3. Performance test of type B SAS prototype

Using the Type B SAS prototype, we constructed a servo system for damping (see Figure 2) and conducted performance tests of the prototype: frequency response, active damping performance, vibration isolation performance and long term stability performance. In this section the measured frequency response and active damping performance are summarized.

3.1. Frequency response

To confirm the SAS works as designed we measured transfer functions from actuators to sensors, and compared them with results from a rigid-body simulation [4]. The transfer functions were measured for all the 15 degrees of freedom (DoFs) that we can actuate, in air and with the controls switched off. A typical result is shown in Figure 3, where the blue and red lines show the simulated and measured results. The measured curves fitted well the predictions.
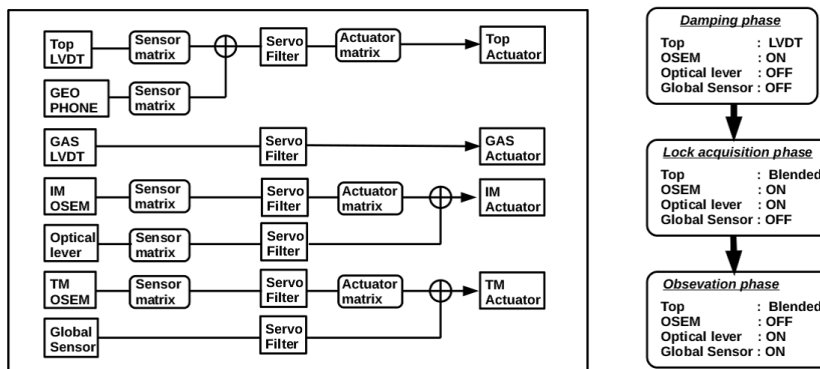

Figure 2. Left: local damping control for performance test of the type B SAS prototype. Signals from photo sensors are used instead of as-yet unavailable main interferometer signals. Right: local control transition toward observation state.

3.2. Active damping performance in damping state

To test if the mechanical resonances of the SAS were damped within 1 min, which is required for KAGRA, by the active controls in the damping state, we measured the $1/e$ damping time with the controls on and off. In this measurement, we obtained the damping time of the mechanical resonances by exciting the system using appropriate actuators and measuring decay signals using

implemented sensors. Also, only modes with resonance frequencies below 20 Hz were measured because of the difficulty in exciting the system above 20 Hz with actuators on the SAS. The results is shown in Figure 4. We found basically the resonances were damped properly. Although a decay time of one mode was slow, we confirmed we could damp within 1 min all the resonances which were likely to disturb lock acquisition and observation. For only one resonance at 0.6 Hz we could not reduce the decay time below 1 min, however, this resonance is hard to excite other than by external disturbance. The mode is concerning with transversal motions of TM and RM. Even if it becomes excited, it cannot affect the lock acquisition unless the amplitude is extremely large, such as 1 mm, which is the requirement of the beam spot fluctuation on the optics of the interferometer.
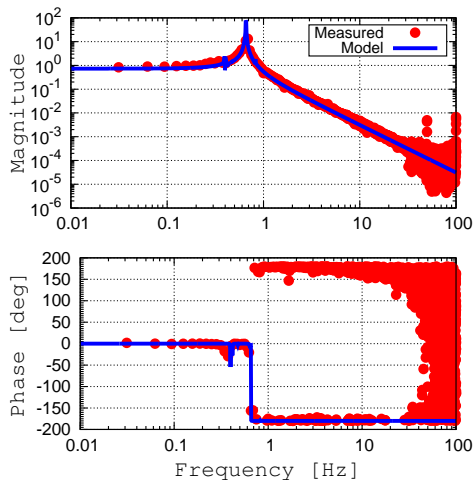

Figure 3. Transfer function of the TM Length DoF in the air

Figure 4. Active damping performance of the prototype

4. Summary

We assembled a Type B SAS prototype and evaluated its performance. From the frequency response test, we confirmed all the components of the SAS were properly suspended. From the active damping performance test, we confirmed we were able to damp the mechanical resonances caused by external disturbances and recover the steady state again within a few minutes.

References
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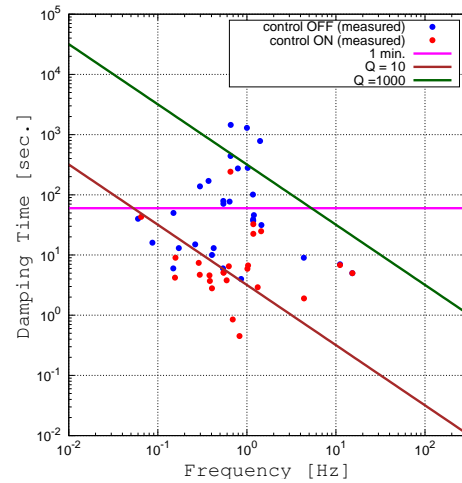[4] Sekiguchi T, 2012, Master's thesis