Recent progress of TAMA300

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Abstract. Current effort of the TAMA project is focused on establishment of the interferometer operation with a new vibration isolation system, called “Seismic Attenuation System” (SAS). The SAS employs a multiple stage structure to realize soft spring for all of directions, as well as utilizes active control systems to stabilize mechanical resonances in the low frequency region below 1 Hz. The SASs were installed for four test masses, resulting in improvement of cavity length fluctuation below 150 Hz. We describe the structure of the SAS and its local active control system, and the status of the interferometer.

1. Introduction
TAMA300 [1] is a laser interferometer gravitational wave detector with 300-m cavity arms, being located at the campus of National Astronomical Observatory of Japan, which is about 20 km away from the center of Tokyo. Purposes of TAMA300 are to develop a detector that is able to catch possible gravitational waves from nearby galaxies, and to establish necessary technologies for future km-class interferometers such as LCGT [2]. The construction of TAMA300 started in 1995. The interferometer operated without power recycling from 1999 to 2001, performing six times of observation runs. Power recycling technique was employed in 2001 so as to improve shot noise level by enhancing the internal laser power in the interferometer. From 2003 to 2004, three times of observations were held with improved sensitivity [3]. With those nine times of observation runs, more than 3000 hours data in total was accumulated [4].

Since 2005, we have been working on the new vibration isolation system, called “Seismic Attenuation System” (SAS). The sensitivity of TAMA300 at around 100 Hz was limited by coupling of alignment sensing noise; in order to improve the sensitivity of TAMA300 in the low frequency band, the control bandwidth of the alignment control should be reduced. For this purpose, we replace the previous vibration isolation system [5] [6] to the SAS. The SAS has a multiple stage structure to realize seismic filtration from the low frequency such as 100 mHz. The SAS was installed for all of four test masses and the tuning of the local control systems for the SAS was completed in the summer of 2007.

Our current efforts are focused on interferometer commissioning. We have established operation of the power recycled interferometer with the SAS although tuning of the interferometer subsystems and of the sensitivity is still in progress. In this article, we explain the structure of the SAS and its local active control system. The status of the interferometer is also described.
2. Seismic Attenuation System

2.1. Mechanical structure

The SAS is a vibration isolation system with a total height of about 2.5 meters, as shown in Figure 1. The SAS was developed by the collaboration of Caltech and TAMA researchers. The design of the structure was based on the prototype experiments [7] [8].

The SAS has a multiple pendulum structure formed by five passive stages: an inverted pendulum (IP) [9], a suspended vertical filter, and a triple pendulum called payload. The IP at the first stage provides horizontal vibration isolation. A resonance of the IP at about 30 mHz was achieved by cancellation between elastic restoring force by flex joints and anti-spring force by the gravity. The concept of the IP is based on the superattenuator of VIRGO [10] [11]. The three IP legs are connected to the top part at which a vertical filter, called Filter-Zero, is placed. Another vertical filter, which is the second stage and called Filter-One, is suspended from the top of the IP. Each of those two vertical filters employs a Monolithic Geometrical Anti-Spring Filter (MGASF) [12] for vertical attenuation. The MGASF utilizes compressed blade springs to make the vertical resonant frequency low, such as 500 mHz. The payload [13], which is suspended from Filter-One, is a triple pendulum formed by a platform, an intermediate mass, and the test mass. The intermediate mass is suspended from the platform using miniature MGASFs for additional vertical isolation. The motion of the intermediate mass is damped by eddy current with permanent magnets flexibly supported from the platform [14]. The test mass is actuated by coil-magnet pairs. The coils are attached on a recoil mass that is also suspended from the intermediate mass, so that the actuation can act only on the differential motion between the recoil mass and the test mass and can not excite other undesirable mechanical modes of the multiple pendulum.
Figure 3. Spectra of the mirror angular fluctuations in the pitch (left) and yaw (right) directions with and without the test mass control. The RMS value of each spectrum integrated from 10 Hz is shown with dashed line. The numbers at the top of each plot show the RMS values of each condition that are derived from the integration from 10 mHz to 10 Hz.

2.2. Local control

In order to ensure the stability of the interferometer, active controls of the SAS is indispensable. The vibration isolation performance of the SAS is essentially provided by low resonant frequencies of the mechanical systems, that are typically below about 1 Hz: The IP and the multiple pendulum have resonant frequency of 0.03–1.6 Hz in the horizontal direction. The MGASFs and the Mini-GASFs has the vertical resonance at 0.5–2 Hz. For the torsional motion, the multiple pendulum has the resonant frequency of 40–500 mHz. It also means that these resonances are easily excited by the seismic motion which has large amplitude in such a low frequency region. In order to suppress the excited motion, three active local controls are applied (Figure 2): an IP control, a torsion control, and a test mass control. All of these control servos are realized by digital control systems based on LabVIEW.

The IP control is the feedback system that senses and suppresses the motion of the IP with the sensors and the actuators placed at the top of the IP. In order to realize the passive isolation performance and the stability at the same time, a two-loop design is used: One loop is an LVDT loop which keeps the position of the IP using position sensors by LVDTs [15] against drift motion. The LVDTs measure the motion of the IP relative to the ground. Therefore, the bandwidth of the LVDT loop is set to be as low as 70 mHz in order to avoid the seismic reinjection from the LVDT loop. The other loop is an ACC loop which damps the inertial motion of the IP using accelerometers [16], thus called inertial damping. The control frequency band of the ACC loop is between 70 mHz and 1.9 Hz. Consequently, this loop suppresses microseismic motion and mechanical reaction of the multiple pendulum.

We take linear combinations of the signals from the sensors and to the actuators so that we can treat the system with three horizontal degrees of freedom as three single degree of freedom systems. This technique to simplify the IP control is called diagonalization [17]. The sensors and the actuators are tri-symmetrically arranged at the top of the IP. Therefore, the sensing and actuation concern with every mechanical eigenmodes all together, making the mechanical response complicated. On the other hand, each of the eigenmodes is purely sensed and actuated by taking proper linear combinations of the sensor signals, as well as those of the actuator signals. As a result, the mechanical responses of the system are remarkably simplified.
The torsion control is to damp the low-frequency torsion resonances of Filter-One and the payload independently from the IP control. It is difficult for the inertial damping to suppress these torsion modes because they do not appear in the top of the IP; the Filter-One is suspended from the IP by a single wire, and therefore the torsional motion of Filter-One is decoupled from that of the IP. The resonant frequencies of the torsion modes are as low as 40 mHz and 80 mHz. Moreover they have high quality factors such as 100. Consequently, these resonances have long decay times of the modes. Once they are excited, the angular motion of the test mass grows up and disturbs interferometer operation about half an hour. The torsion control system senses the angular motion of Filter-One by reflective photosensors, and actuates the rotation of the IP by the IP coil-magnets. The servo filter is designed so that the feedback can be effective only at the mode frequencies so as not to inject unnecessary sensing noise to the system. As a result, the effective quality factors of the modes less than 10 were achieved, which corresponds to the decay time of several minutes.

The test mass control is to stabilize the angular motion of the mirror. The angular sensor is an optical lever that is fixed on optical windows of the vacuum chamber. A visible laser light illuminates the mirror. The position of the reflected beam is detected by a position sensitive detector. The actuator is the coil-magnet pairs of the test mass. Figure 3 shows the angular spectra of the test mass in the pitch and yaw directions. The free-running angular motions in RMS for pitch and yaw are 1.4 $\mu$rad$_{\text{RMS}}$ and 12 $\mu$rad$_{\text{RMS}}$, respectively. Although these values are too large for the interferometer operation, they are able to be suppressed by control loops with the bandwidth of several Hz, as the fluctuation power is concentrated below 1 Hz. The resultant angular fluctuation with the active control is 0.23 $\mu$rad$_{\text{RMS}}$ and 0.16 $\mu$rad$_{\text{RMS}}$ for pitch and yaw, respectively, as shown in the same figure. Since these values are about 5 times smaller than that with the previous vibration isolation system, they are considered enough for establishing the interferometer operation. In addition, this measurement let us expect to reduce the alignment noise contribution to the gravitational wave channel. For the optical lever control, the transfer function of the digital servo is configured by precise placement of poles and zeros so that large peak structures in the spectra can be suppressed.

Once these local control systems are configured to be functioning, the interferometer operation
3. Interferometer status

After the shaking down of the SAS and its local control systems, the power recycled operation of the 300-m Fabry–Perot Michelson interferometer has become available. Figure 5 shows the current configuration of the TAMA interferometer. The light source is an injection locked Nd:YAG laser with output power of 10 W [18]. The laser beam is injected into a 10-m mode cleaner cavity for spatial filtering and frequency stabilization [19] [20]. The main interferometer is a Fabry–Perot Michelson interferometer with power recycling [21]. For the length sensing, the Pound-Drever-Hall technique [22], Schnupp modulation [23] [24], and third harmonic demodulation [25] are used. For the global alignment sensing, wave front sensors (WFS) are used [26] [27].

The lock acquisition procedure is as follows. First, all of the local controls are turned on and the operating point of the optical lever is adjusted so as to realize a good alignment of the arm cavities. Next, the recycled Michelson interferometer is locked with the third harmonic demodulation signals by actuating the beamsplitter and the recycling mirror. One of the arms is, then, locked with the Pound-Drever-Hall signal by actuating the laser frequency. Finally, the other arm cavity is locked by actuating the corresponding input test mass of the cavity. Once the lock is acquired, the operating points of the optical levers are slowly controlled to fulfill the operating point of the WFSs. In order to obtain gravitational wave signals as low noise as possible, the cavity control signals are switched to the bright and dark port signals. The beamsplitter control signal is also switched to the bright port signal with fundamental frequency demodulation.

For the lock acquisition of the secondary arm, a digital control system is used. The digital filter is a TMS320C6713 DSP based system with a sampling rate of 200 kHz. The achieved control bandwidth was 800 Hz, which was comparable with that of the previously-used analog servo. This system uses three techniques that assist the lock acquisition: Error signal normalization, error signal triggering, and adaptive servo filtering. The error signal of the cavity come to be available. The longitudinal fluctuation of the 300-m Fabry–Perot cavity was measured by a length correction signal. The displacement spectrum below 10 Hz is shown in Figure 4. By comparison with the spectrum with the previous suspension system, it was confirmed that the length fluctuation with the SAS is improved above 0.1 Hz. Not only the power spectrum, but also the RMS motion of the cavity length is improved from 1.4 µmRMS to 0.84 µmRMS.

Figure 5. Schematic diagram of the current interferometer configuration of TAMA300

Figure 6. Schematic view of the pre-emphasis/de-emphasis configuration for the alignment and length control loops by digital filters.
Figure 7. Current strain sensitivity of TAMA300 (red) and the alignment noise level (blue), which is currently limited by DAC noise at around 100Hz. The previous best sensitivity (black) is also shown.

lock is normalized by the transmitted power to extend the linear range of the error signal. This helps the servo system to increase the interaction time by a factor of about three. The error signal triggering turns on and off the servo loops by looking at the light level of the resonance. This is useful to eliminate unwanted feedback by the modulation sidebands and the higher order spatial modes, resulting in reduction of the kick by those spurious signals and allowing us to increase the feedback gain. The adaptive servo filtering is to increase the low frequency control gain when the lock acquisition is detected. We use an adaptive change of the digital filter coefficients in order to realize smooth change of the filter response for glitch-less gain boosting.

Increasing use of digital filters makes the interferometer operation flexible and easier. Digital filters, however, have 100 to 1000 times worse noise levels at the input and the output compared to well-designed analog circuits. In order to avoid coupling of these noises to the interferometer sensitivity, pre-emphasis/de-emphasis (PE/DE) technique is employed (Figure 6). A pair of filters with complementary shapes is inserted into the feedback loop. This enhances the noise immunity, while the total servo shape is preserved. For the input side of the digital system, the PE filter with the gain of $G_{\text{PE}}$ is used, while inserting the anti-PE filter into the digital filter with the gain of $G_{\text{antiPE}} = 1/G_{\text{PE}}$. This reduces the effective noise level of the ADC by a factor of $G_{\text{PE}}$. Similarly, for the output, the anti-DE filter which has gain of $G_{\text{antiDE}}$ is used, while inserting the DE analog filter with the gain of $G_{\text{DE}} = 1/G_{\text{antiDE}}$. This reduces the effective noise level of the DAC by a factor of $G_{\text{antiDE}}$. Since these filters reduce the sensing and actuation range of the control system, those PE/DE filters are switched off during the lock acquisition, while they are turned on after the lock is acquired.

The current sensitivity of TAMA300 is shown in Figure 7. Sensitivity improvement up to 150 Hz was confirmed although further tuning of the interferometer system is needed for the higher frequency band; not the full of the light is received at the dark port to avoid saturation. We analyzed the level of the alignment control noise, and found the DAC noise of the alignment control loop is very close to the noise level at 100 Hz. Further improvement of the alignment
noise is expected by employing additional DA noise reduction and activation of fast WFS servos in stead of the optical lever.

4. Summary
We have been working on the improvement of the vibration isolation system by SAS, Seismic Attenuation System, since 2005. The SASs were installed for the four test masses in 2007. They are now functioning after the shaking down of the local control systems. We have confirmed that the angular fluctuation of the mirror is concentrated below 1 Hz. This leads us to the reduction of the alignment control bandwidth and eventually to the improvement of the sensitivity at about 100 Hz. The improvement of the length fluctuation above 0.1 Hz was confirmed by an arm cavity measurement. The decrease of the RMS mirror motion has also been observed.

With sufficiently stable performance of the SAS, the power recycled Fabry–Perot Michelson interferometer is able to operate. The lock of the arm cavity was established with help of digital filters. The sensitivity of the interferometer was measured, and then improvement up to 150 Hz was confirmed. Improvement in the higher frequency band will be achieved by further tuning of the interferometer system such as injection of the full light to the dark port photodetector and refinement of the angular control servos.

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