Control system for the Seismic Attenuation System (SAS) in TAMA300

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Abstract. A new seismic isolation system, TAMA Seismic Attenuation System (TAMA-SAS), was installed to TAMA300 in order to improve the sensitivity at low frequencies. Inertial damping is one of the hierarchical control systems of the TAMA-SAS which are employed to give full play to its ability. We have established two servo loops to control the Inverted Pendulum (IP) which composes the SAS. One is the servo loop using LVDT position sensors to keep the position of the IP. The other is the inertial damping which uses accelerometers to control the inertial motion of the IP for the horizontal direction. The fluctuation of the IP was reduced using our servo system. In addition, reduction of angular and longitudinal fluctuation of the mirror was also confirmed. These results indicate that the control for the IP properly works and the isolation performance of the TAMA-SAS was improved.

1. Introduction

In order to improve the sensitivity of TAMA300 [1] in the low frequency band, the SASs (Seismic Attenuation Systems) were employed to isolate the test masses from ground motion. As one of the problems to overcome for the improvement, we had to reduce the alignment control noise which dominated the sensitivity of TAMA300 below 200Hz[2]. It was required for the suspension system to have high isolation performance for the suspended mirror in the angular directions as well as the longitudinal direction along the cavity below 10 Hz. The TAMA-SAS could accomplish these requirements by its multiple suspension system. However, the multiple structure has many resonances below 1 Hz and makes amplification of the seismic motion. Therefore it is important to damp such resonances by control systems. In this paper, we focus on the active control system of an Inverted Pendulum (IP) which is the first stage of multiple passive filter chain. We also show results that the inertial damping of the IP reduces the mirror fluctuation with respect to both of the angular and longitudinal directions.

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The TAMA-SAS is a vibration isolation system with a total height of about 2.5 meters, formed by 5-stage passive isolators (Figure 1), which is an IP, a vertical filter, and a triple pendulum called payload. This structure was based on the prototype experiments about the performance evaluation for its design [3][4]. The IP[5] at the first stage is horizontal attenuation. A low resonant frequency of the IP (about 50 mHz) was realized by cancellation between restoring force of flex joints and anti-spring effect by the force of gravity. The concept of the IP is based on the superattenuator[6] of VIRGO[7]. Three IP legs are combined by the first vertical filter which contains Monolithic Geometrical Anti-Spring Filter (MGASF)[8] for vertical attenuation. The MGASF utilizes compressed blade spring to make the vertical resonant frequency low, such as 500 mHz. The payload[9], which is suspended from the second vertical filter, has functions of eddy current damping on an intermediate stage, vertical isolation by miniature MGASFs, and test mass actuation from a recoil mass.

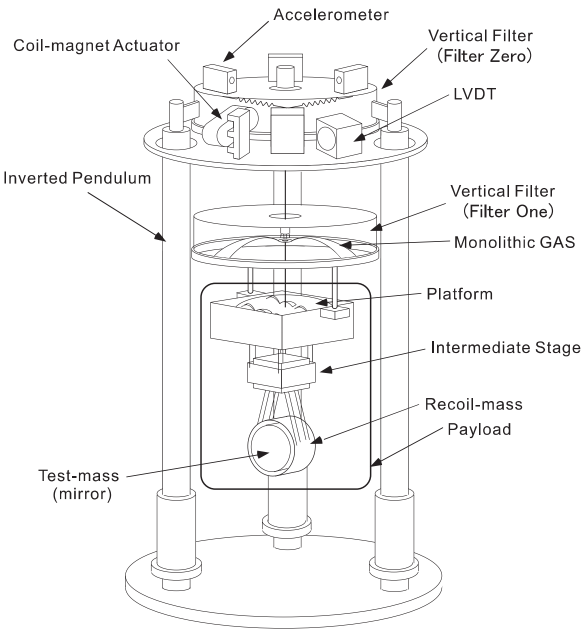


Figure 1. Schematic view of the TAMA-SAS.

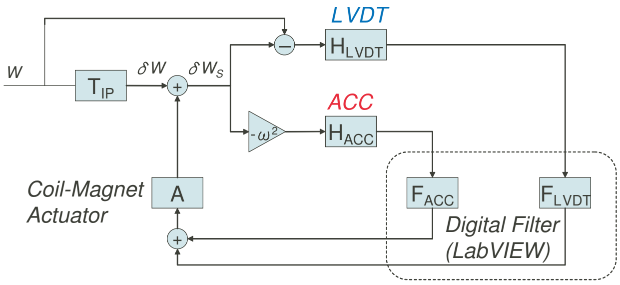


Figure 2. Block diagram of the servo loop to control the IP.
T_{IP} indicates a transfer function of the inverted pendulum from the ground to the top of the IP. Seismic motion (W) is transmitted to the IP (δW), then is controlled (δW_S) by this servo system. H, F, and A indicate transfer functions of the sensors, the filters, and the actuator, respectively.

2. Control of Inverted Pendulum

2.1. Control Scheme

The essential vibration isolation performance of the IP is provided by the soft springs of the components as described in the previous section. This also means that the seismic motion is amplified at the resonant frequencies. In terms of the IP, the stability is degraded by the resonances of the IP itself, as well as parasitic resonances which appear as a reaction of the further filter stages. In order to realize the passive isolation performance and the stability at the same time, we employed the active control system with two feedback loops; one is the servo loop to keep the position of the IP, and the other is the servo loop to damp the inertial motion. Particularly, the later is so-called inertial damping.

Figure 2 shows a block diagram of the servo control for the IP. The motion of the IP is controlled using two servo loops which consist of two sensors, two digital filters, and coil-magnet actuator[10] which is in common. A similar control has been also performed in VIRGO[11]. The sensors are Linear Variable Differential Transformers (LVDTs)[12] and accelerometers

(ACCs)[13]. The LVDTs measure relative displacement between the IP and the frame fixed to ground. This means that the position control using the LVDTs is referred to the ground, and therefore can re-inject seismic noise above 50 mHz which is the resonant frequency of the IP. On the other hand, the ACCs measure horizontal acceleration of the IP with regard to the inertial frame. Therefore the control with the ACCs is free from the seismic re-injection.

In order to simplify the control system, the eigen modes of the motion is separately sensed and actuated. For this purpose, we take linear combinations of the sensor signals, as well as those of the actuator signals. This scheme is called the diagonalization. The IP has three degrees of freedom in horizontal direction (Figure 3). They are decomposed to the eigen modes which consist of two translation modes (X, Y) and one rotation mode (θ). By diagonalizing these sensors and actuators, we can control a motion of the IP with an independent mode.

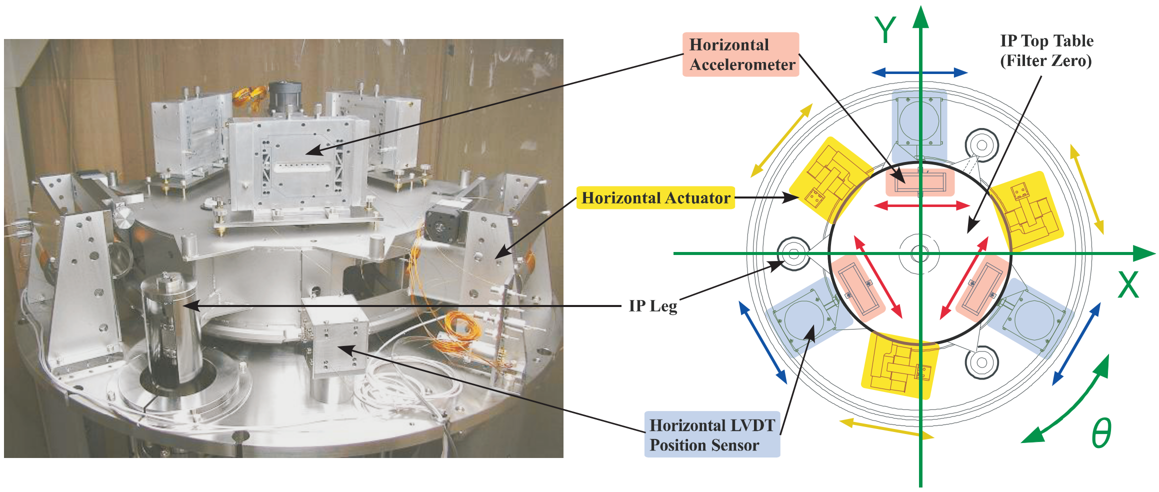


Figure 3. Arrangement of the sensors and the actuators on the top of the IP. The sensors and the actuators are aligned in a symmetric way. Sensing and actuating directions are denoted by arrows along with them. The eigen modes of the IP are denoted by X, Y, and θ.

2.2. Servo Design of the Control for the IP

We designed these two servo loops taking the characteristics of the sensors into account. The open loop transfer function is designed as Figure 4. These are calculated using measured transfer functions from the actuators to the sensors and using designed filters. The servo of the Y mode was designed with the same concept for the X mode. Similar design was used for each of the other SASs.

The LVDT loop has a role to prevent the drift of the IP below 70 mHz in the directions of Y. The LVDT control for the θ direction is not used as the drift motion in θ was found to be small enough. The LVDT loop is designed to be stable by itself such that the loop is kept stable even if the other loop fails. The unity gain frequency and the phase margin are 0.2 Hz and 36 degree, respectively. To prevent seismic noise re-injection, the control gain above 70 mHz was set as low as possible using roll-off filters.

The ACC loop role is to reduce the fluctuation of the IP at resonant modes of the seismic attenuation chain. The control has a bandwidth between 70 mHz and 1.9 Hz in the translational Y direction. The phase margin at the unity gain frequency of 1.9 Hz is to be 71 degrees, and at the crossover frequency of 70 mHz with the LVDT loop is to be 50 degrees. The bandwidth of the control was optimized so as not to include the region of the sensor noise. Consequently, the inertial damping is applied to the micro-seismic motion between 0.1 Hz and 0.4 Hz, and the reaction from the suspended loads, which appears as parasitic resonances at 0.7 Hz and 1.1 Hz. The θ direction was designed to damp only the fundamental resonance at 0.5 Hz.

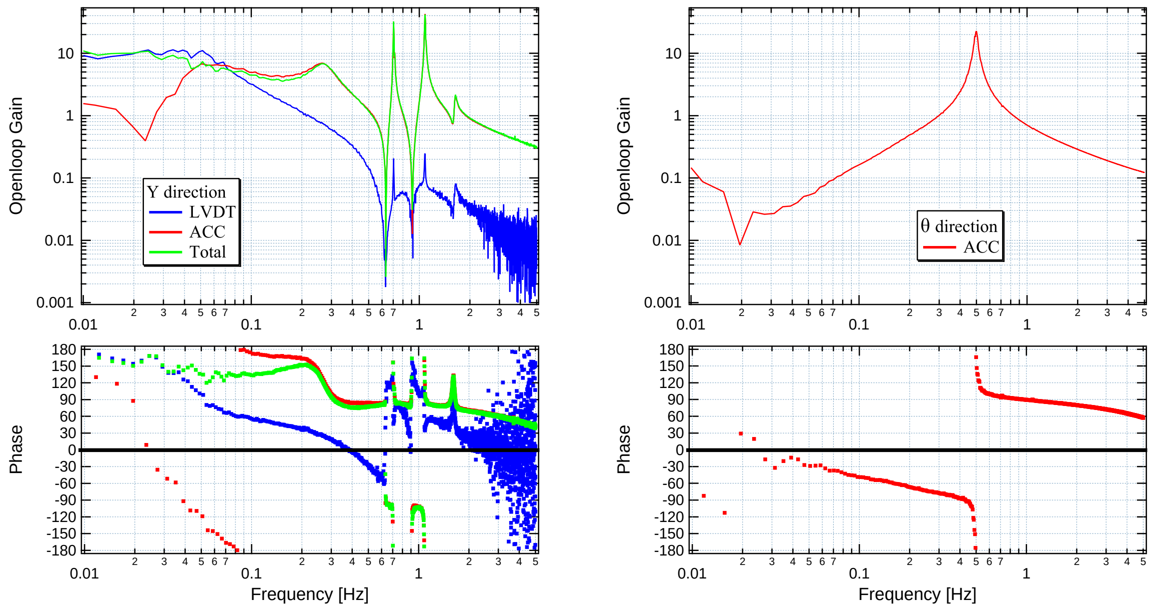


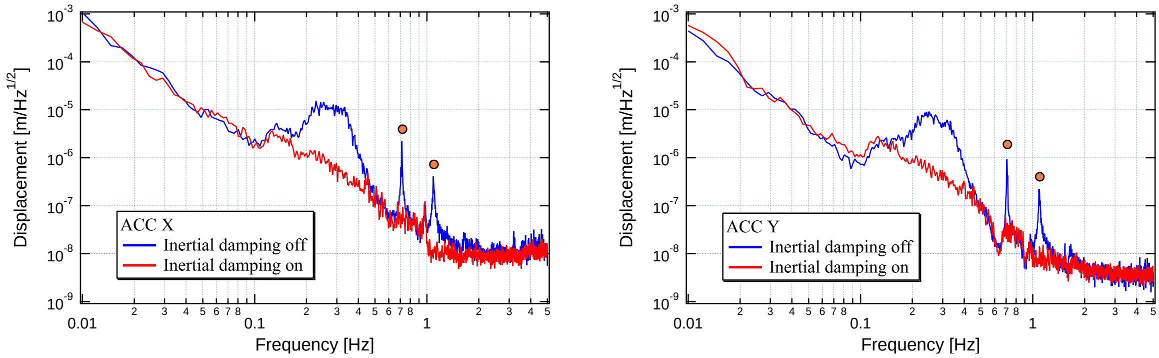
Figure 4. Servo design for the control of the IP in the in-line front SAS.
Left : Open loop gain of each loop in the direction of Y-mode. Right : Open loop gain in the direction of θ-mode. These are calculated using measured transfer functions from the actuator to the sensor and using designed filters.

3. Results of Control for the IP

In order to confirm the functionality of the control for the IP, we observed the ACC signals with and without inertial damping. Then, the mirror fluctuation was measured with respect to the angular and longitudinal directions. It is a kind of out-of-loop evaluation to confirm that the fluctuation of the IP was actually reduced.

First, the comparison of the accelerometer output for each mode was performed with and without the inertial damping, as shown in Figure 5. Using the inertial damping we were able to reduce the fluctuation of the IP at the micro-seismic peak (0.1-0.4 Hz) by as much as 28 dB at the parasitic resonances (near 0.7 Hz and 1.1 Hz) by 35 dB in the X and Y direction as well as the resonance of the rotational eigen mode of the attenuation chain denoted as θ (0.5 Hz) by 40 dB. These results are in accord with the reductions expected from our servo design. This means that the control for the IP is properly carried out.

Second, the angular fluctuation of the test mass was measured by an optical lever with and without the inertial damping, as shown in Figure 6. Ideally, the translational motion of the IP should not be concerned with the angular motion of the mirror. However, the reduction of the angular fluctuation was observed in several frequencies. The angular fluctuation of the mirror was reduced by as much as 38 dB in the micro-seismic and the parasitic region by the inertial damping. We believe that the mirror angular motion in these frequencies was mainly dominated by the coupling from the translational motion of the IP. Hence the improvement of



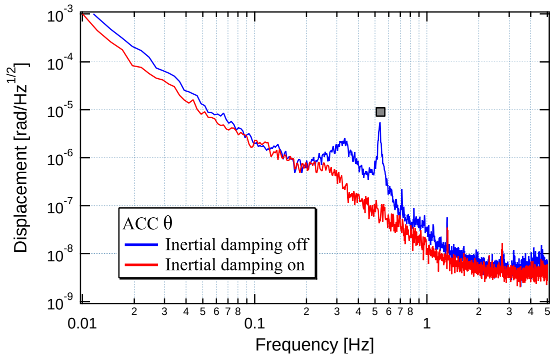


Figure 5. Displacement of the IP in each mode with and without inertial damping. These were measured by the accelerometer (ACC) as an in-loop evaluation. The orange circles indicate the parasitic resonances. The grey square indicates the fundamental mode of θ direction.

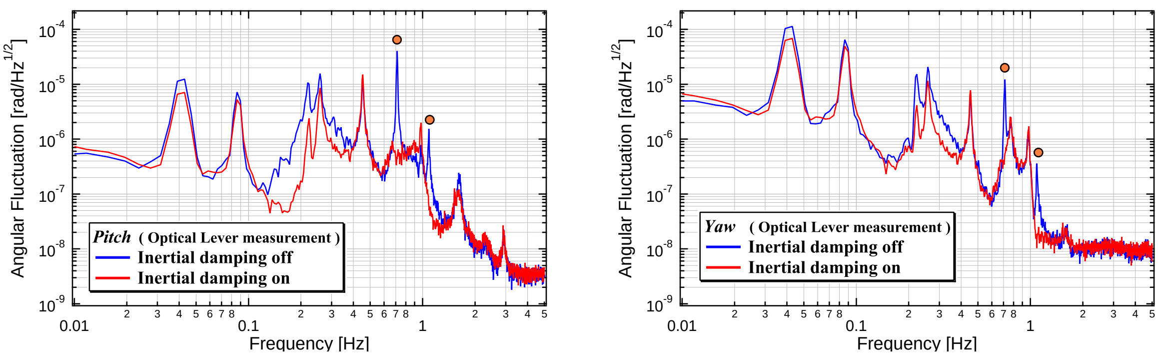


Figure 6. Angular fluctuation of the mirror.
Left: The direction of pitch, Right: The direction of yaw. These were measured by an optical lever. The orange circles denote the resonances corresponding to the parasitic resonances.

the fluctuation of the mirror is due to the control for the IP in the translational directions. On the contrary, the resonance at 0.45 Hz was not reduced because the resonance stems from the MGASF in the vertical direction; it can be damped with a separate damping loop. Although we damped the rotation mode of the IP (0.5 Hz) in the direction of θ, it did not appear in the yaw direction because of isolation by the torsion mode. Two peaks at 40 mHz and 86 mHz are due to the torsion modes of the MGASF and the payload. It is likely that the peaks in the pitch direction are coupling from the yaw direction by, for example, the misalignment of the optical lever.

Third, the length fluctuation of the 300-m cavity was measured with and without the inertial damping, as shown in Figure 7. The inertial damping also reduced the length fluctuation of the cavity by 32 dB in the same region where the displacement of the IP was reduced. We were able to confirm the improvement of the fluctuation at the frequency of the mode coupling from the rotation mode θ (0.5 Hz). The inertial damping remarkably reduced the RMS motion from 6.2 μm to 1.0 μm for frequency region from 50 mHz to 2 Hz.

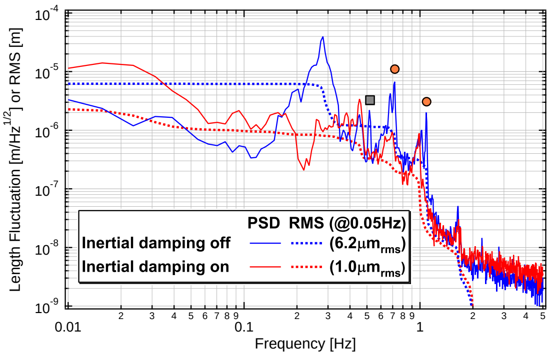


Figure 7. Length fluctuation of the 300-m cavity with the SAS pair.
The length fluctuation was measured by a feed back signal to the laser to lock the Fabry-Perot cavity which consists of the SAS pair. The RMS was integrated below 2 Hz because the signal in the region above 2 Hz was dominated by the frequency noise. The orange circles and the grey square denote the resonances corresponding to the reduced resonances in the IP.

4. Summary

We have established the control system for the IP with the two-loop servo using the sensors of the LVDT and the ACC. It is confirmed that these controls were properly carried out. The inertial damping suppress the micro-seismic peak and the parasitic resonances in the X and Y directions as well as the resonance of the θ direction. The reduction of the angular and longitudinal fluctuation of the mirror was also confirmed. This means that we were able to improve the performance of the TAMA-SAS. The smaller angular fluctuation of the mirror enables us to make the bandwidth of the alignment control narrower. Therefore we expect that this result leads to the reduction of the alignment control noise.

5. Acknowledgments

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