Improvement of Vibration Isolation System for TAMA300

Ryutaro Takahashi‡**, Koji Arai, and the TAMA collaboration**
National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan

Abstract. The vibration isolation system for TAMA300 has a vibration isolation ratio large enough to achieve the requirement in the observation band around 300 Hz. At the lower frequency range, it is necessary to reduce the large fluctuation of mirrors for stable operation of the interferometer. With this aim, the mirror suspension systems were modified and an active vibration isolation system using pneumatic actuators was installed. These improvements contributed to the realization of a continuous interferometer lock for more than 24 hours.

1. Introduction

The development of TAMA300, an interferometric gravitational wave detector with two 300 m long base lines, is well into development in Japan[1]. The target sensitivity of TAMA300 is $h_{\mathrm{rms}} = 3 \times 10^{-21}$ at 300 Hz (the band width 300 Hz), corresponding to a horizontal displacement noise $\delta\tilde{x} = 5 \times 10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. The ground vibration level at Mitaka, the site of TAMA300, however is $\delta\tilde{x} \simeq 10^{-12}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 300 Hz. Therefore the mirrors which form the interferometer, need to be isolated from ground motion by a factor of more than 10^8 around 300 Hz.

Figure 1 shows the vibration isolation system in a vacuum chamber. The mirror is hung in a suspension which stands on a vibration-isolated breadboard supported by three legs, each consisting of a three-layer stack[2]. The mirror suspension is a double pendulum with flexible eddy current damping[3]. Since the previous suspension had a large pitch fluctuation, it was difficult to lock the interferometer, especially in the day time. Therefore the suspensions were modified as shown in the next section. The whole system in the vacuum chamber is controlled by pneumatic actuators attached to the legs of the baseplate via the double balanced bellows. Installation of the pneumatic actuators is an important improvement described in this paper.

Using measured transfer functions of the stack and the mirror suspension prototypes, we estimated the seismic noise that appeared in the interferometer. Figure 2 shows the estimated seismic noise and the present mirror displacement noise observed in TAMA300 with the alignment noise spectrum. Two kinds of estimation are shown: one is horizontal mirror displacement due to horizontal seismic motion, the other is

---

‡ ryu.takahashi@nao.ac.jp

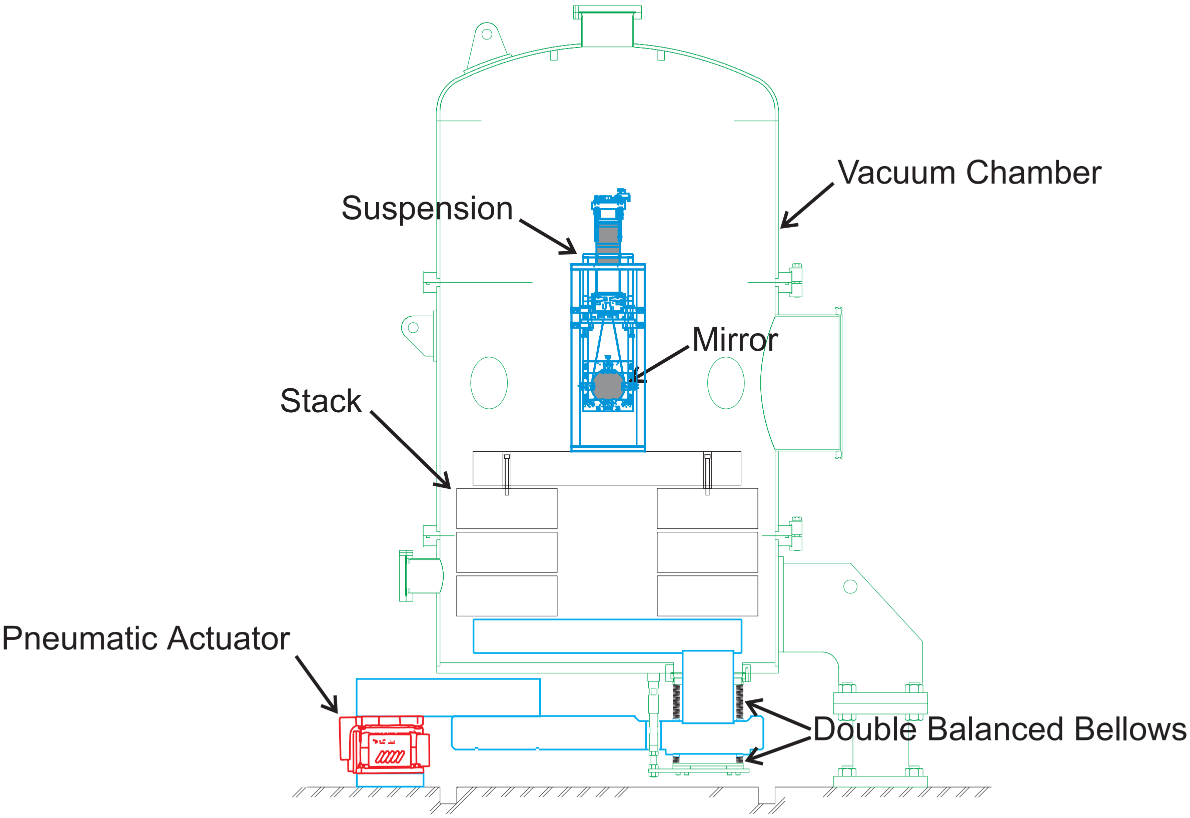

Figure 1. Longitudinal cross section of the vibration isolation system in a vacuum chamber. Normally each stack supports one mirror suspension. The whole system in the vacuum chamber is controlled by pneumatic actuators attached to the legs of the baseplate via the double balanced bellows.

horizontal mirror displacement coupled from vertical seismic motion. Noise coupled from the vertical motion, with a magnitude of $10^{-16}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 40 Hz, is larger than straight horizontal noise. We confirmed that the seismic noise was dominant at frequencies less than 30 Hz. At frequencies greater than 30 Hz, the alignment noise was dominant. As a result the vibration isolation system for TAMA300 has a vibration isolation ratio large enough to achieve the requirement.

2. Modification of the Mirror Suspension System

The mirror suspension system was developed in consideration of mirror control, vibration isolation, and thermal noise. Its basic design is a double pendulum. Strong permanent magnets, arranged around the upper mass of the double pendulum, damp the fundamental mode (1 Hz) of the pendulum by an effect known as eddy current damping. If the magnets were fixed to the suspension point, the isolation performance of the pendulum would be disturbed by the damping magnets coupling to the upper mass. Therefore the permanent magnets are also suspended by the thin rods.

This suspension system had a high-$Q(\simeq 30)$ pitch mode resonance at 5 Hz. In

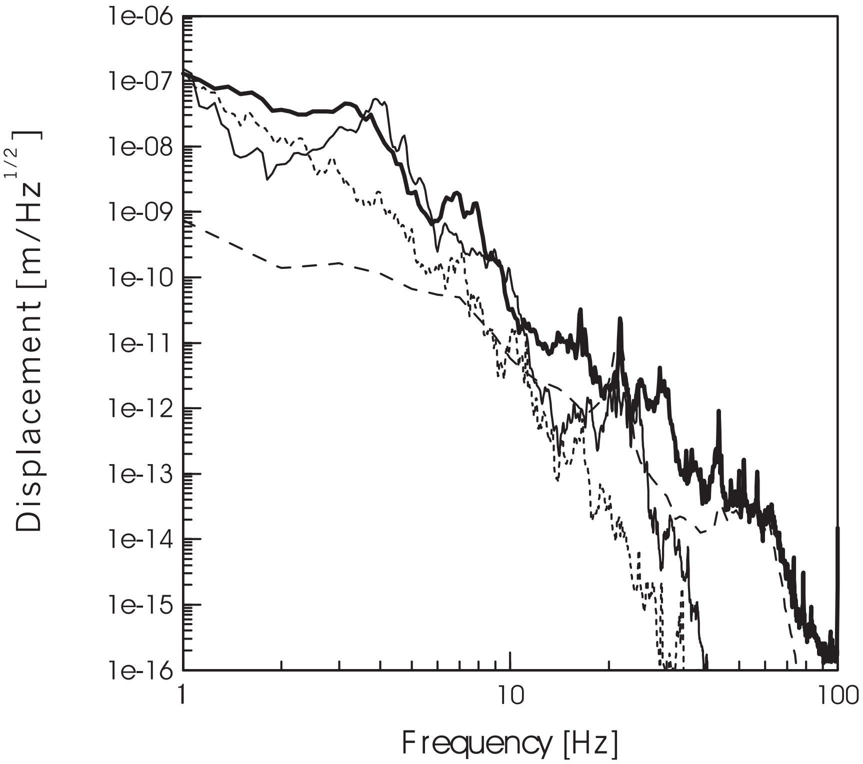

Figure 2. Estimated seismic noise (normal line) and observed displacement noise in TAMA300 (thick line) with the alignment noise spectrum (dash line). The normal solid line shows horizontal mirror displacement due to horizontal seismic motion. The normal dotted line shows horizontal mirror displacement coupled from vertical seismic motion.

order to realize stable operation even in the night time, it was necessary to set the unity gain frequency (UGF) of the mirror alignment control above 10 Hz. In this case, noise induced from the alignment system dominated the sensitivity of TAMA300 in the observation band.

We moved the resonant frequency of the pitch mode from 5 Hz to 1.8 Hz, by decreasing the gap between the wires suspending the upper mass from 9 cm to 2 cm. Since this mode strongly couples to the upper mass around 1 Hz, the 1.8 Hz resonance was effectively damped. Figure 3 shows the modified angular fluctuation of the mirror pitch mode. The RMS of angular fluctuation was reduced from 4 mrad to 0.8 mrad as a result of the modification to the suspension. This reduction of the angular motion allowed us to use the alignment control with the UGF of 5 Hz together with a 10-pole Chebyshev low-pass filter having a 60 Hz cut-off frequency. With this alignment servo setup, we improved the sensitivity of TAMA300 around 100 Hz by a factor of 10[4].

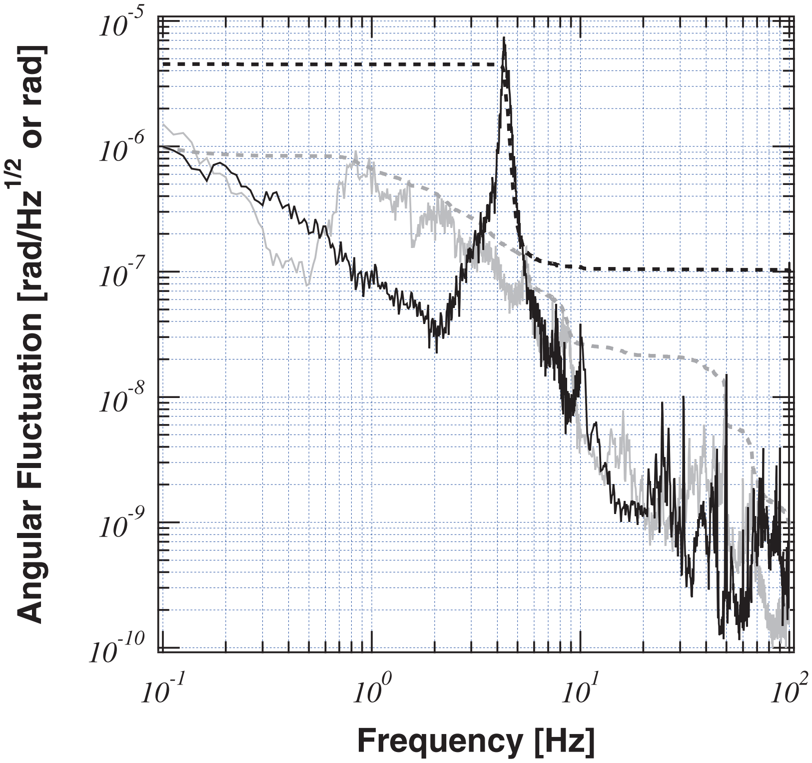

Figure 3. Modified angular fluctuation of the mirror pitch mode. Black lines show angular fluctuation (solid) and its RMS (dash) for the old suspension system. Gray lines show angular fluctuation (solid) and its RMS (dash) for the modified one. The RMS was reduced from 4 mrad to 0.8 mrad.

3. Active Vibration Isolation

The active isolation system was installed below the baseplate outside of each vacuum chamber. The stack system is put on the upper baseplate, which was supported by the rigid stem of the double balanced bellows connecting to the lower baseplate fixed to the ground (Figure 1). The baseplate is mechanically isolated through the bellows from the chamber and is free from atmospheric pressure which is sustained by the bottom of the bellows rigidly connected with two rods to the bottom of the vacuum chamber[5]. This mechanism was useful to introduce the actively controlled actuators.

We selected Tokkyokiki Corp.'s $\alpha 2$ as an active vibration isolation system. This consists of four compact units with two dimensional pneumatic actuators. Originally the vibration isolation system was supported by three legs symmetrically placed. The $\alpha 2$ system needs four units, so the position of the legs was rearranged. The system was installed keeping the total weight of the stack and the suspension setup at 1,500 kg. The $\alpha 2$ has three control loops.

- Absolute vibration feedback loop from 1 to 20 Hz.
- Ground vibration feed-forward loop from 0.5 to 50 Hz.
- Position feedback loop from DC to 0.1 Hz.

The signals from the acceleration sensors on the suspended parts of the pneumatic actuators are processed by a DSP and fed back to the pneumatic actuators to control all 6 degrees of freedom (DOF). The signals from acceleration sensors on the ground are fed forward to the pneumatic actuators for additional control of 3 DOF: X, Y (horizontal), and Z (vertical).

Measured transfer functions showed a fundamental passive resonance at 9 Hz for X and Y, and at 5 Hz for Z. When the system was installed other mechanical resonances around 100 Hz were found. These were suppressed by digital filters in the DSP. The measured isolation ratio with active control was $10 \sim 20$ dB at frequencies greater than 1 Hz for all 6 DOF. The DC position of the suspended parts are maintained by a feedback system using eddy current position sensors.

4. Stability of the Interferometer

Stability of the interferometer depends on RMS amplitude of seismic vibration. RMS of ground vibration from 1 to 10 Hz at the site of TAMA300 is $5 \sim 10$ mgal in the day time (9 to 17 o'clock) and $2 \sim 5$ mgal in the night time (18 to 8 o'clock) as shown in Figure 4. This difference is due to human activity. For example, day time excitation is not observed on Sundays. In the day time, the interferometer was unstable without the active isolation systems, frequently losing lock.

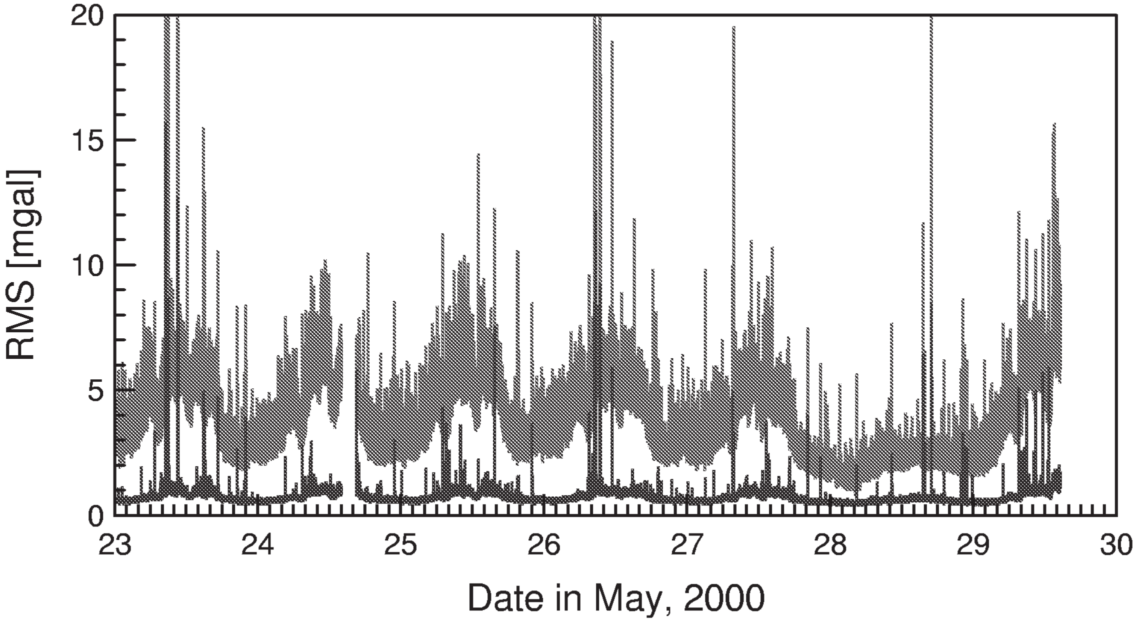

Figure 4. Trend of the horizontal RMS amplitude of the ground (gray line) and the controlled parts (black line) from 1 to 10 Hz in May, 2000. The day time excitation was not observed on Sunday, the 28th.

The active vibration isolation system described above drastically improved this condition. The RMS amplitude of the controlled parts was kept less than 2 mgal except for occational non-gaussial noise spike. Both the improvements of the mirror suspension and the installation of the active vibration isolation system contributed to allowing full-time observation with TAMA300. Actually 24.8 hours operation without unlock of the interferometer was realized in a test run (5 - 6 June, 2001). This record corresponds to twice length of the previous longest lock stretch of 12.8 hours.

5. Summary

We confirmed that seismic noise is dominant only at the frequencies less than 30 Hz. The mirror suspension systems were modified to damp the large pitch motion of the mirrors. Since the large resonances disappeared, an alignment control with a low UGF was realized in order to reduce the alignment noise. An additional $10 \sim 20$ dB of isolation was obtained with active control using pneumatic actuators. The RMS amplitude (1 to 10 Hz) of seismic vibrations was improved from $5 \sim 10$ mgal to less than 2 mgal by the active control system. Full-time operation of TAMA300 was made possible owing to these improvements.

Acknowledgements

We wish to thank the people of Tokkyokiki Corp. for work on the installation of the pneumatic actuators. This research is supported by a Grant-in-Aid for Creative Basic Research of the Ministry of Education, Sports, Culture, Science and Technology (No. 09NP0801).

References

[1] Ando M *et al* 2001 *Phys. Rev. Lett.* **86** 3950
[2] Takahashi R, Kuwahara F and Kuroda K 1997 *Proc. of the TAMA Int. Workshop on Gravitational Wave Detection (Saitama)* ed K Tsubono, M-K Fujimoto and K Kuroda (Tokyo: Universal Academy Press) p 95
[3] Araya A, Arai K, Naito Y, Takamori A, Ohishi N, Yamamoto K, Ando M, Tochikubo K, Kawabe K and Tsubono K 1997 *Proc. of the TAMA Int. Workshop on Gravitational Wave Detection (Saitama)* ed K Tsubono, M-K Fujimoto and K Kuroda (Tokyo: Universal Academy Press) p 55
[4] Ando M and the TAMA collaboration 2001 to be published in this issue
[5] Ogawa Y, Michizono S and Saito Y 1993 *Vacuum* **44** 465