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Anatomy of the TAMA SAS seismic attenuation system

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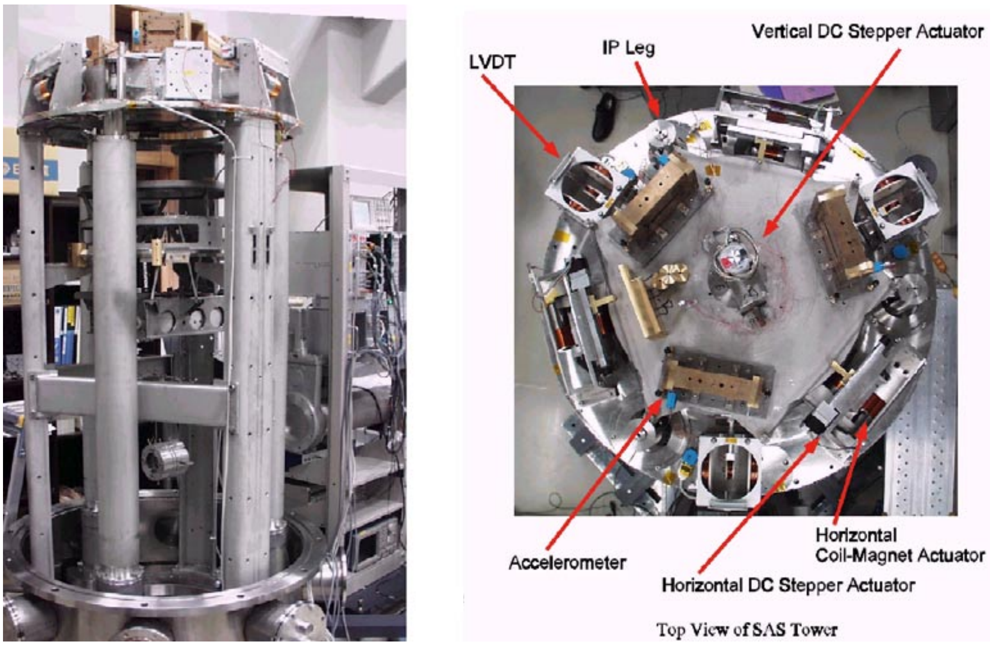

(a) (b)

Figure 1. Photographs of the TAMA SAS prototypes while being installed within the vacuum chambers of the TAMA 3 m interferometer at Tokyo University. (a) (Side view) The IP leg in the front and the MGASF filter holding the suspension andmirror mass. The beamline is towards the rear-right direction. (b) (Top view) The novel monolithic accelerometers and the LVDT sensors with well visible coils.

and it was developed based on the LIGO prototype[1] [5, 6]. Interesting and relevant results on passive seismic attenuation were published by Australian groups [25–27]. We designed the system so that the transmitted noise level due to external mechanical disturbances is well below the internal thermal noise level of the mirrors for frequencies above 10 Hz. The SAS is a mainly passive system [7]. However, we employ an active damping system [9, 10, 19], which suppresses some of the structural/internal resonances of the constituents. Images and schematics of the TAMA SAS towers are shown in figures 1 and 2. Detailed mechanical designs can be obtained from [8]. The SAS system is fully UHV compatible and it can be accommodated within the vacuum volume available at TAMA300.

The horizontal vibrations are very effectively attenuated by a tri-legged ultra low frequency (30 mHz) inverted pendulum (IP) [11]. An inertial damping system employing very sensitive accelerometers [12] and voice coil actuators [13] is used to attenuate system resonances at low frequencies (from ∼10 mHz to ∼6 Hz). The position relative to ground is sensed by a set of LVDT sensors [14]. The vertical disturbances are attenuated via series of monolithic geometrical anti-spring filters (MGASF) [15–18]. A multiple pendulum mirror suspension is attached to the quiet end of the MGASF chain to provide final attenuation of better than 10^{-12} at the mirror position above a few Hz. The very low frequency control of the IP allows simple payload positioning from the suspension

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[1] Document reference numbers starting with LIGO point to documents available from the LIGO archives at http://admdbsrv.ligo.caltech.edu/dcc/.

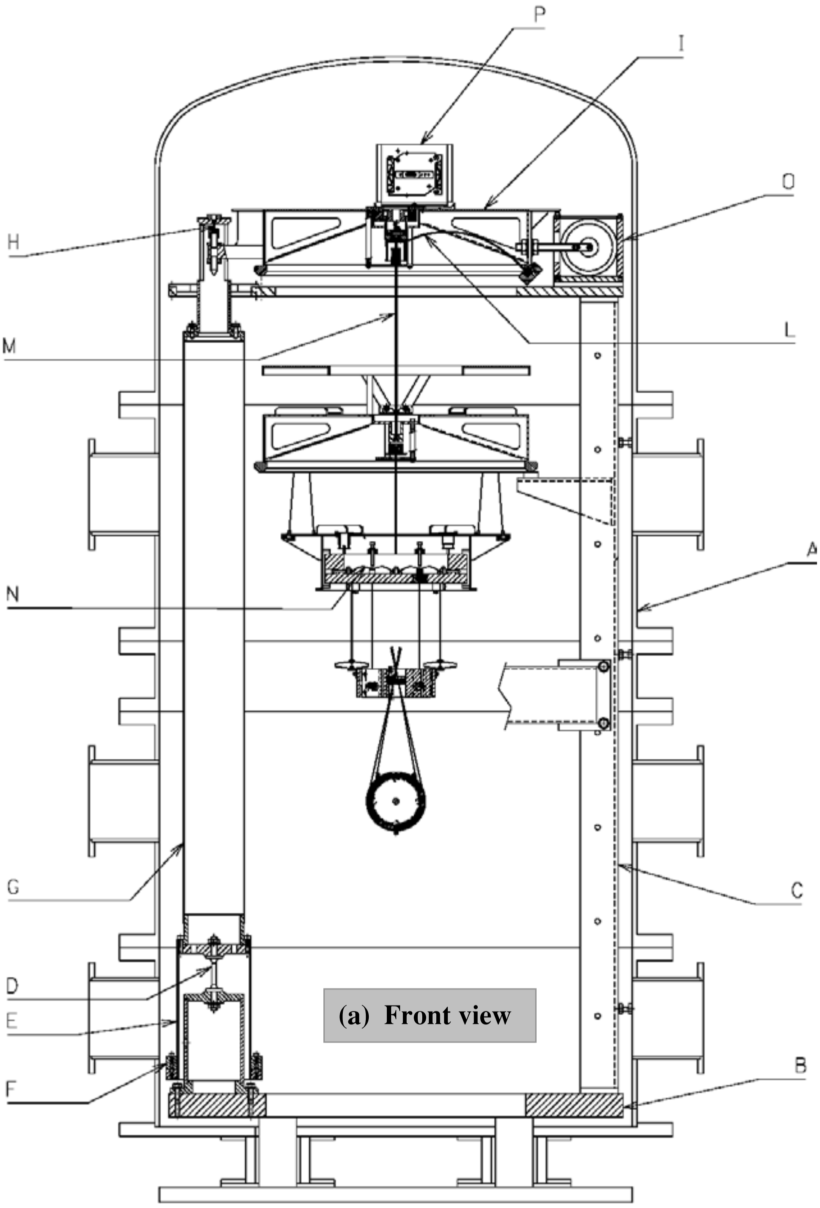

Figure 2. These mechanical drawings illustrate the complex anatomy of the TAMA SAS system ((a) front view, (b) side view, (c) top view). The major components, starting from the noisy ground towards the quiet test mass are the following: vacuum chamber (A), support and safety structure (C), base plate (B), IP flex joints (D), 'bell' (E) holding the counter weights (F), IP tubular legs (G), secondary flex joints (H) joining the IP top and the first MGASF (I), horizontal accelerometer (P), horizontal (O) and vertical (R) LVDT position sensor, voice coil actuators (T), horizontal (U) and vertical (S) positioning stage, balancing springs (Q), Maraging steel MGASF blades (L), long pendulum wire (M) holding the second MGASF, advanced suspension (N).

point, thereby minimizing the payload residual motion and misalignment, which must be picked up by the mirror suspension controller. The passive nature of the SAS ensures

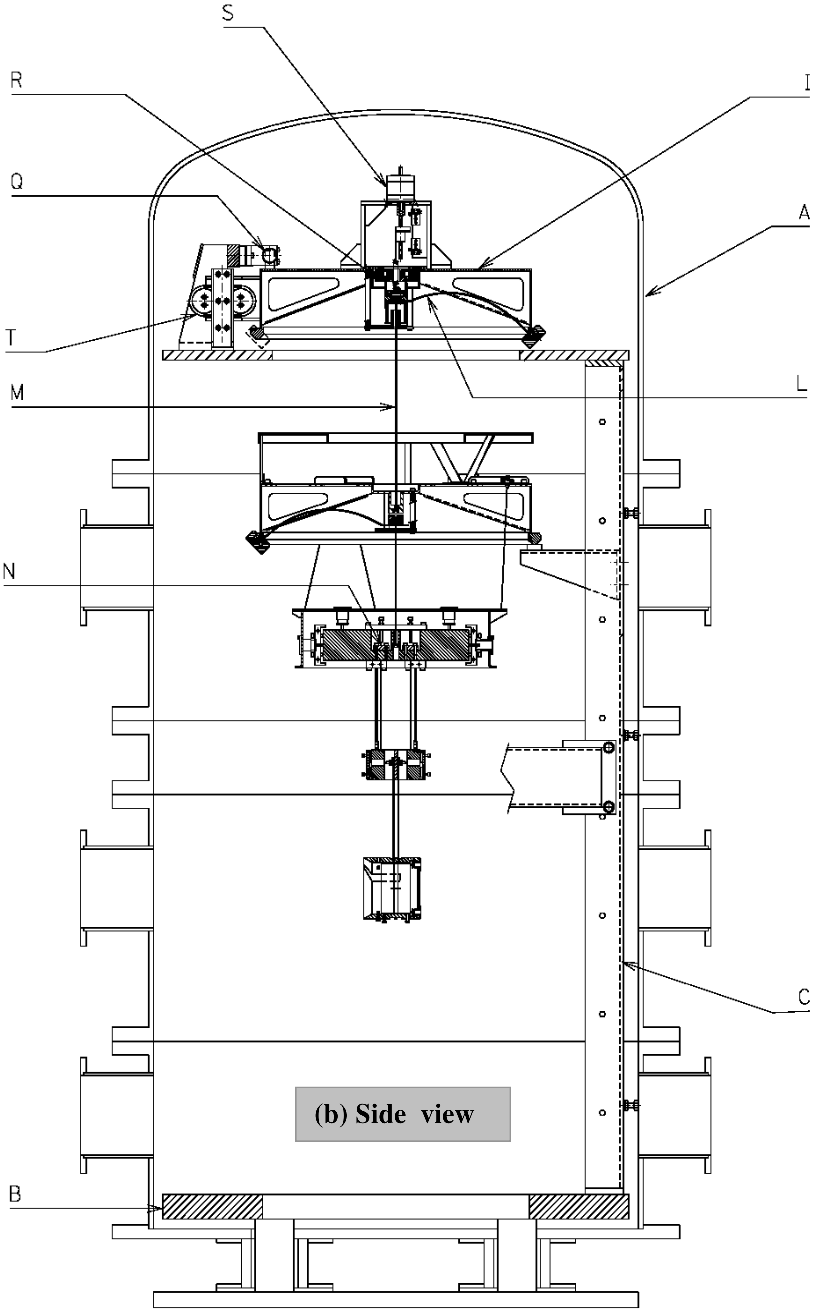

Figure 2. (Continued.)

reliable attenuation free of disturbances due to external couplings and electronic noise. Some of the important characterization results on the IP and MGASF are shown in figures 3–5.

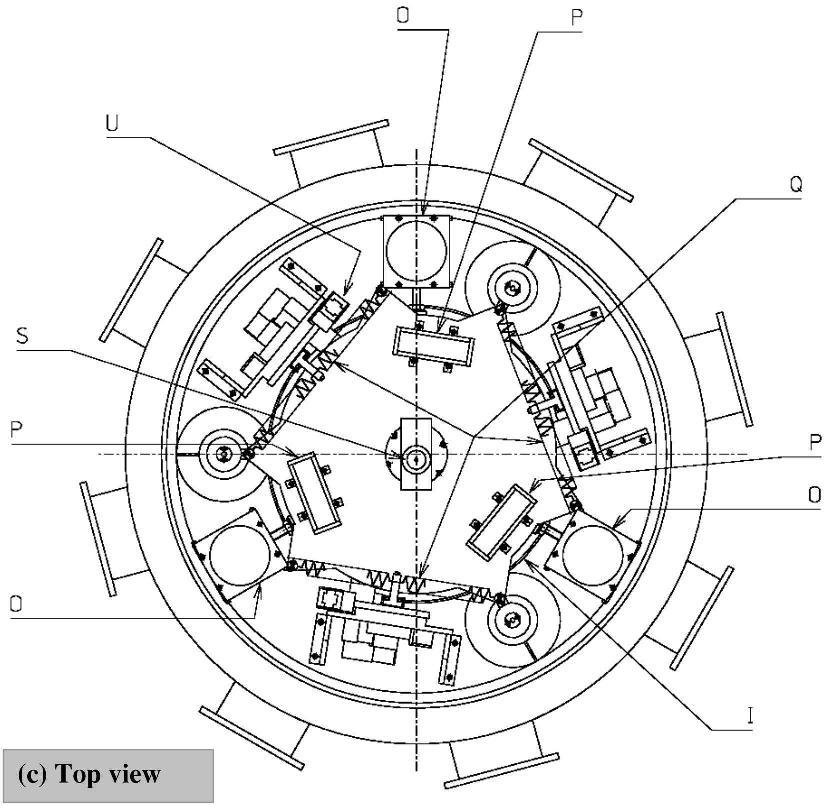

Figure 2. (Continued.)

2. Anatomy and characterization results on the SAS system

It is important to draw attention to some of the basic properties, requirement and constraints on the widely used passive mechanical attenuation systems to fully appreciate the SAS performance and understand its structure. Passive seismic attenuation chains and multiple pendulum mirror suspensions for GW interferometers are usually constructed utilizing various (30–100 cm long) pendula. These chains have rigid body resonances between 0.5 and 1 Hz and they typically have good quality factors. Seismic excitation in this frequency range can excite these resonances to large excursions that might overwhelm the mirror's position control actuators. The reduction of the dynamic range required from the mirror actuators is fundamental from the point of view of reducing the noise introduced by the control system. It is consequently very important to shield the suspensions from seismic excitations in the low frequency regime via pre-isolators. We must also provide a mechanism to drain the energy that seeps into or is stored in the chain rigid body modes. It is important to provide means for very low frequency positioning of the mirror suspension with a resolution in the order of a fraction of a micron. It is necessary to have a system capable of absorbing fairly large perturbations from macroscopic seismic events without disrupting the mirrors. Since the core optics of GW detectors is accommodated in ultra high vacuum (UHV), it is mandatory for the full attenuation system, from sensors to bolts, to be UHV compliant.

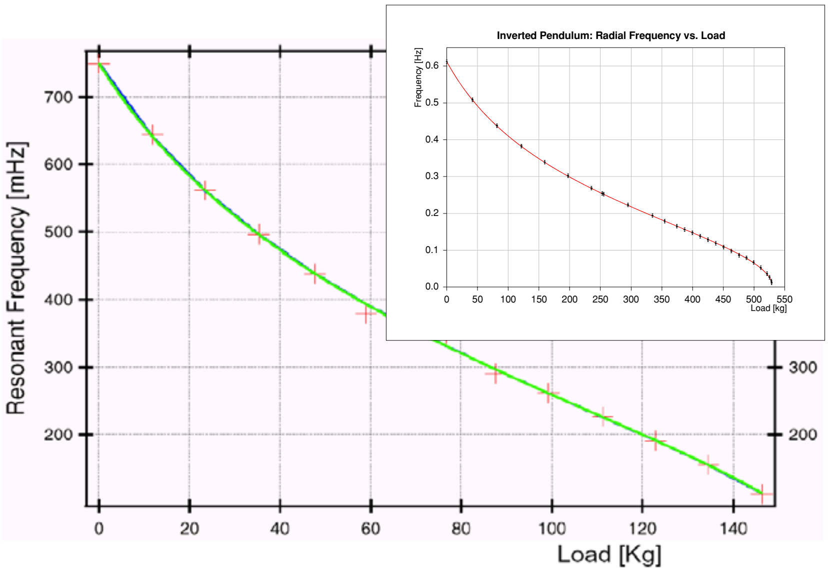

Figure 3. Inverted pendulum radial resonance frequency versus load at the top of the IP. The graph shows the behaviour of the TAMA SAS IP; as the load increases the observed resonance frequency decreases dramatically. Our model (solid curve) is in very good agreement with the measurements (+ marks). The inset illustrates the general shape of the resonant frequency versus load behaviour of inverted pendula for a very broad range of loads, from virtually no load to critical load. (The measurements for the insert were performed on the large LIGO tower.)

All of these requirements are achieved in the horizontal plane by our tri-legged inverted pendulum system. In the vertical direction these functions are performed by our low frequency monolithic geometric anti spring filters [15–18]. The two remaining tilt modes are not relevant since the chain is suspended by single wires that do not transmit tilt in the first approximation.

Figures 1 and 2 show our design, consisting of an IP holding stages of geometrical anti springs filters (GASF), to isolate the test mass suspension from ground noise [8]. The ultra-low frequency IP also suppresses the horizontal microseismic peak. The three legs of the IP are supported by Maraging steel flextures, providing restoring force the leg. These flex joints serve as a pivot point for the pendulum, while their restoring force is reduced due to the gravitational anti-spring effect. The quality factor of the IP is compatible with structural damping according to our measurements on an earlier IP prototype. The main resonance frequencies of the IP can be tuned to very low values, by carefully adjusting its load as it is shown in figure 3. The internal resonances of the legs were modelled, designed and tested to be above 50 Hz. Besides the slightly non-degenerate main resonance frequencies of the IP, the leg, payload and flex joint non-uniformity shows up as a tilt of the pendulum under heavy loads. To centre the pendulum, we designed a finely tunable spring-actuator system made of a set of three soft tangential springs, mounted at 120°. The middle of each spring is attached to a motorized stage to allow very low frequency IP positioning (figure 2). The force balance of these springs can be fine-tuned to precisely correct any misalignment or imperfection. This balancing system can also be used to correct slow tidal or weather-induced tilts. The use of these springs does not compromise the efficiency of the system and can be considered as a small addition to the spring constant of the flextures. The extremely soft IP requires minimal control force, which simplifies actuation at very low frequencies. Each leg has a counterweight

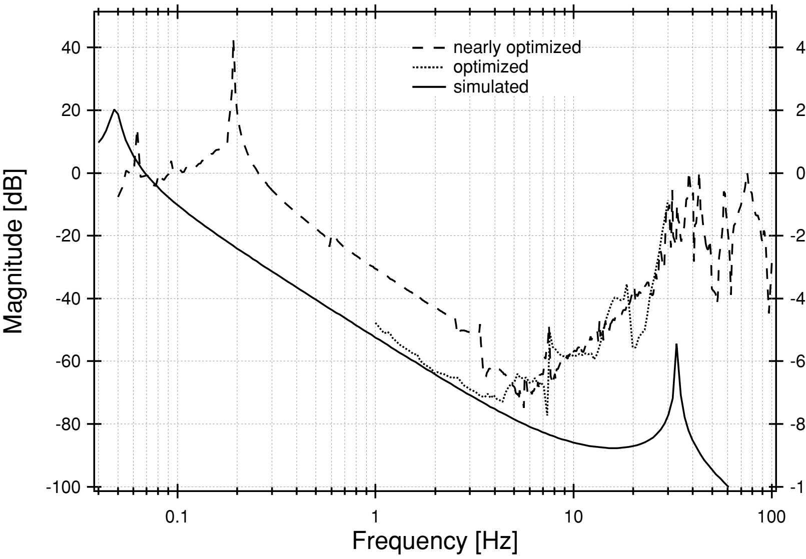

Figure 4. Horizontal transfer function measurements for different tunings of the centre of percussion balance. Note that the achieved attenuation is better than 60 dB in the 2–5 Hz region. These results (dotted curve) are in good agreement with our models (smooth curve) and fit our expectations. The curves were obtained from a real life test of the full structure. The base plate was mounted on low friction high-flow oil bearings. The excitation signal, up to 10 mm at low frequency, was injected at the base plate via strong voice coil actuators. The transfer functions are based on signals from accelerometers mounted on the base plate and on the top of the first MGASF filter. The structure above 10 Hz on this figure is an experimental artifact. It is due in part to the limited sensitivity of our accelerometers and in part to the steel weights placed but not rigidly mounted on top of the first MGASF filter stage to set the IP resonance frequency. The resonance at 33 Hz in the simulation is the pendulum resonance of the secondary flex joint at the top of the IP. The IP counterweight was brought close to optimal ('nearly optimized curve'), whereas for convenience the IP main resonant frequency was tuned to 200 mHz instead of the 45 mHz nominal working frequency. This makes the tuning procedure much easier and significantly faster. Once the optimal counterweight is found, retuning the IP below 45 mHz automatically produces an attenuation plateau at or below the minimum achieved level (simulation and optimized curve).

mounted on a 'bell' extending below the joint to allow precise centre of percussion tuning, to optimize good attenuation up to the first leg internal resonance. With the proper centre of percussion balancing we achieved attenuation plateaus as low as –60 dB (in the 2–5 Hz region in figure 4). According to our simulations this attenuation saturation plateau extends up to the first internal mode of the leg, beyond which the leg does not behave like a rigid body anymore. At the top of the IP, the payload is attached to the legs through short wires, acting as a second flex joint.

We used a cascade of MGASF filters attached to the top of the IP to achieve vertical attenuation of $\sim$–60 dB per filter (figure 5). The second MGASF filter is attached to the stage above with a single long wire, which provides additional horizontal attenuation while decoupling the tilt modes. The second stage of vertical filters supports the complex mirror suspension described by Takamori *et al* in this issue [19, 20].

It is not possible to provide detailed analysis of each subsystem in this paper, however, the articles, reports and drawings listed as references give a comprehensive coverage of SAS subsystems [24].

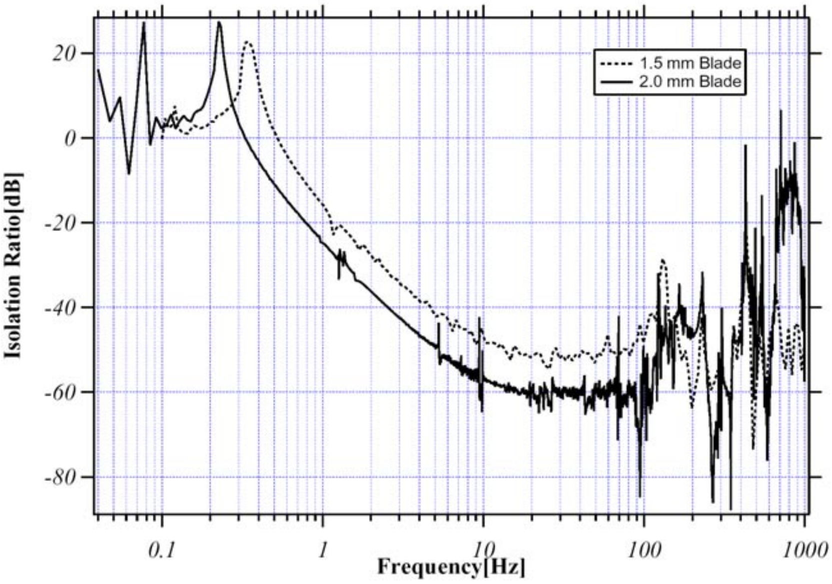

Figure 5. Vertical transfer function measurements of a single MGASF stage. Note that we achieved 60 dB of attenuation between 20 and 80 Hz with only a single stage (lower curve 2 mm blade)! These measurements were performed on a test bench where a softly mounted MGASF filter was excited by a voice coil actuator. The transfer functions are based on the output of two accelerometers, one rigidly joined to the rim of the filter body whereas the other was mounted on the test mass below.

3. Conclusions

We have developed and built a high performance seismic attenuation system, utilizing novel geometries and high quality materials. We used only passive attenuation for the critical frequencies above 10 Hz, while active damping is relegated for lower frequencies. We built proof-of-concept prototype for LIGO and two working systems for TAMA. We demonstrated that our system is scalable and it provides the required attenuation both horizontally and vertically. Our isolation towers and novel suspensions [21–23] are currently being tested in the TAMA 3 m interferometer at the University of Tokyo and they are approved as the baseline design for the TAMA300 interferometer upgrade and the LCGT (large cryogenic gravitational wave telescope).[2]

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[2] Comprehensive description of LCGT project is available at http://www.icrr.u-tokyo.ac.jp/gr/LCGT.pdf

References

[1] DeSalvo R *et al* 1999 Performances of an ultralow frequency vertical pre-isolator for the VIRGO seismic attenuation chains *Nucl. Instrum. Methods Phys. Res.* A **420** 316–335

[2] Ballardin G *et al* 2001 Measurement of the virgo superattenuator performance for seismic noise suppression *Rev. Sci. Instrum.* **72** 3643

Ballardin G *et al* 2001 Measurement of the virgo superattenuator performance for seismic noise suppression *Rev. Sci. Instrum.* **72** 3652

[3] Losurdo G *et al* 1999 An inverted pendulum pre-isolator stage for VIRGO suspension system *Rev. Sci. Instrum.* **70** 2507–15

[4] Losurdo G 1998 Ultra-low frequency inverted pendulum for the VIRGO test mass suspension *Tesi di Dottorato di Ricerca in Fisica Scuola Normale Superiore di Pisa-Classe di Scienze (Italia, Ottobre 1998)* webpage http://www.virgo.infn.it/thesis/DottLosurdo.ps

[5] Barton M *et al* Proposal of a seismic attenuation system (SAS) for the LIGO advanced configuration (LIGO-II) *LIGO Internal Note* T990075-00 1999

[6] Bertolini A, Cella G, Chenyang W, DeSalvo R, Kovalik J, Márka S, Sannibale V, Takamori A, Tariq H and Viboud N 2001 Recent progress on the R&D program of the seismic attenuation system (SAS) proposed for the advanced gravitational wave detector, LIGO II *Nucl. Instrum. Methods* A **461** 300–3

[7] Bertolini A *et al* 1999 New seismic attenuation system (SAS) for the advanced LIGO configurations (LIGO2) *Proc. 1999 Amaldi Conf.* (Pasadena, CA)

[8] Takamori A, Gennaro G, Zelenova T and DeSalvo R 2001 TAMA seismic attenuation system (SAS) tower mechanical drawings, LIGO-D-010249-00-R

[9] Losurdo G 1999 Inertial control of the Virgo superattenuators *Proc. 1999 Amaldi Conf.* (Pasadena, CA)

[10] Losurdo G, Calamai G, Cuoco E, Fabbroni L, Guidi G, Mazzoni M, Stanga R and Vetrano F 2001 Inertial control of the mirror suspensions of the VIRGO interferometer for gravitational wave detection *Rev. Sci. Instrum.* **72** 3653

Losurdo G, Calamai G, Cuoco E, Fabbroni L, Guidi G, Mazzoni M, Stanga R and Vetrano F 2001 Inertial control of the mirror suspensions of the VIRGO interferometer for gravitational wave detection *Rev. Sci. Instrum.* **72** 3661

[11] Márka S, Sannibale V, Takamori A, Tariq H, Viboud N, Chenyang Wang, Bertolini A, Cella G and DeSalvo R Inverted pendulum as low frequency pre-isolation for advanced gravitational wave detectors *Nucl. Instrum. Methods* in preparation (IP mechanical details available at LIGO-D-010240-00-R)

[12] Bertolini A 2001 High sensitivity accelerometers for gravity experiments *Doctoral Thesis Universita' di Pisa* (accelerometer details are available at LIGO-D-010244-00-R)

[13] Chenyang Wang, Tariq H, DeSalvo R, Iida Y, Márka S, Nishi Y, Sannibale V and Takamori A Constant force actuator for gravitational wave detector's seismic attenuation systems (SAS) *Nucl. Instrum. Methods* Submitted (LIGO- P010026-00-D)

[14] Tariq H *et al* The linear variable differential transformer (LVDT) position sensor for gravitational wave interferometer low-frequency controls *Nucl. Instrum. Methods* submitted (LIGO-P010035-00-D) (LVDT electronic and mechanical details can be found at LIGO-D-010243-00-R and LIGO-D-010248-00-R)

[15] Bertollini A, Cella G, DeSalvo R and Sannibale V 1999 Seismic noise filters, vertical resonance frequency reduction with geometric anti-springs: a feasibility study *Nucl. Instrum. Methods* A **435** 475–83

[16] Sannibale V, Cella G, DeSalvo R, Tariq H, Viboud N and Takamori A Seismic attenuation performance of the first prototype of a geometric anti-spring filter *Nucl. Instrum. Methods* submitted

[17] Sannibale V, Cella G, DeSalvo R, Márka S, Tariq H, Viboud N and Takamori A A new seismic attenuation filter stage (MGASF) for advanced gravitational interferometer detectors *Nucl. Instrum. Methods* submitted (MGASF mechanical details are available at LIGO-D-010241-00-R)

[18] Sannibale V *et al* Monolitic GAS blades *Nucl. Instrum. Methods* (GASF mechanical details are available at LIGO-D-010242-00-R)

[19] Takamori A *et al* Mirror suspension system for the TAMA SAS *Class. Quantum Grav.* this volume

[20] Takamori A, Gennaro G, Zelenova T and DeSalvo R 2001 TAMA seismic attenuation system (SAS) mirror suspension system (SUS) mechanical drawings (LIGO-D-010250-00-R)

[21] Arai K, Takamori A, Naito Y, Kawabe K, Tsubono K and Araya A 1996 *Proc. TAMA Int. Workshop on Gravitational Waves Detection* (*Saitama, Japan*, 1996)

[22] Tsubono K, Araya A, Kawabe K, Moriwaki S and Mio N 1993 *Rev. Sci. Instrum.* **8** 64

[23] Takamori A, Bertolini A, Cella G, D'ambrosio E, De Salvo R, Sannibale V and Viboud N 1999 *Proc. 2nd TAMA Int. Workshop on Gravitational Wave Detection* (*Tokyo, Japan*, 1999)

[24] DeSalvo R 2001 LIGO-II seismic attenuation system (SAS) test tower mechanical drawings listing (LIGO-T-10131-00-R)

[25] Winterflood J and Blair D G 1998 A long-period vertical vibration isolation for gravitational wave detection *Phys. Lett.* A **243** 1

[26] Winterflood J, Zhou Z B and Blair D G 2001 Ultra-low residual motion suspension system *Proc. 2nd TAMA Int. Workshop on Gravitational Wave Detection (National Olympics Memorial Youth Center Tokyo, Japan Oct. 19–22 1999) (Tokyo)* Universal Academy) pp 301–10

[27] Winterflood J *et al* High performance vibration isolation using springs in Euler column buckling mode *Class. Quantum Grav.* this volume