Recent Results of a Seismically Isolated Optical Table Prototype Designed for Advanced LIGO

Virginio Sannibale[1], Benjamin Abbott[1], Yoichi Aso[3], Valerio Boschi[1,4], Dennis Coyne[1], Riccardo DeSalvo[1], Szabolcs Márka[3], David Ottaway[2], and Alberto Stochino[2,4]

[1]California Institute of Technology, 1200 E California Blvd, MC 18-34, Pasadena, CA
[2]Massachusetts Institute of Technology, 185 Albany St, NW 22-295, Cambridge, MA
[3]Columbia University, Physics Department, 1538 W 120 St, New York, NY
[4]University of Pisa, Physics Department, Largo Bruno Pontecorvo 3, Pisa, Italy

E-mail: `vsanni@ligo.caltech.edu` `DCC LIGO-P070127-00-Z`

Abstract. The Horizontal Access Module Seismic Attenuation System (HAM-SAS) is a mechanical device expressly designed to isolate a multipurpose optical table and fit in the tight space of the LIGO HAM Ultra-High-Vacuum chamber. Seismic attenuation in the detectors' sensitivity frequency band is achieved with state of the art passive mechanical attenuators. These devices should provide an attenuation factor of about 70dB above 10Hz at the suspension point of the Advanced LIGO triple pendulum suspension. Automatic control techniques are used to position the optical table and reduce the low frequency rms motion. Here, we report the main results obtained from the full scale prototype installed at the MIT LIGO Advanced System Test Interferometer (LASTI) facility. Seismic attenuation performance, control strategies, improvements and limitations are also discussed.

1. Introduction

Advanced LIGO (AdLIGO) is the first major upgrade to the LIGO gravitational wave interferometers [1]. The sensitivity goals of the detectors are chosen to enable the advance from plausible gravitational wave detection to likely detection and rich observational studies of sources. Advanced LIGO promise an improvement over initial LIGO in the limiting sensitivity by more than a factor of 10 over the entire initial LIGO frequency band. It also increases the bandwidth of the instrument to lower frequencies (from ∼40 Hz down to ∼10 Hz) in order to allow the detection black holes inspirals and unmodeled transient sources. These sensitivity goals require an instrument limited only by fundamental noise sources over a very wide frequency range. In particular, since the low frequency performance of ground based gravitational wave detectors is mainly limited by seismic and anthropogenic noise, mechanical isolators are required in order to obtain the design sensitivity.

2. HAM-SAS

HAM-SAS is a passive seismic attenuation system which is designed to provide 70-80 dB of horizontal and vertical attenuation above 10 Hz [2]. It has been expressly conceived to support

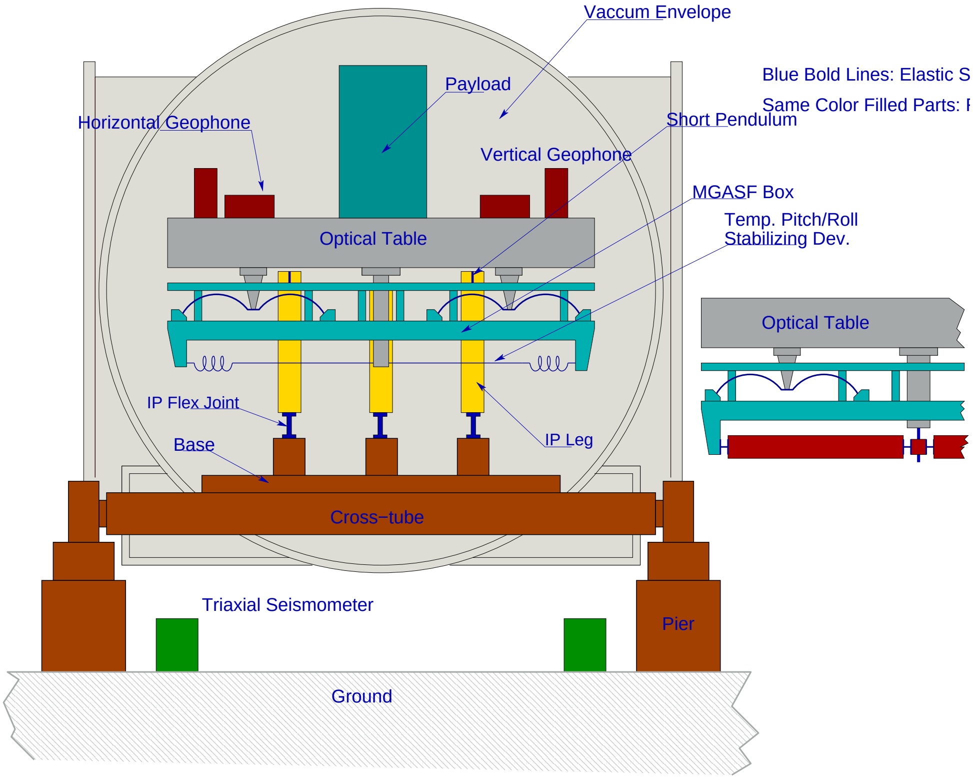

Figure 1. Sketch of HAM-SAS mechanical system, and the improved pitch/roll stabilizing device of the optical table. Blue bold lines indicate elastic structures, same color filled parts indicate rigid structures.

the optical benches of the so called Horizontal Access Module vacuum chamber (HAM) of the future Advanced LIGO interferometers.

Two types of tunable mechanical harmonic oscillators are used in the system, the inverted pendulum (IP) [3, 4] for the horizontal degrees of freedom (DOFs), and monolithic geometric anti-spring (MGAS) [6, 5] for the vertical DOFs. Both devices exploit their fundamental property that the response of an harmonic oscillator to seismic excitation is equivalent to a second-order low pass filter. Since a real mechanical oscillator always have distributed masses, their response saturates above a critical frequency.

IPs are tunable mechanical oscillators widely used for their good horizontal seismic attenuation performance. They are implemented using hollow cylindrical Aluminum legs and flexible maraging steel joints. Resonant frequencies of tens of millihertz have been routinely reached in other systems. A counterweight placed below the IP pivot point allows the center of percussion (COP) of the system to increase the saturation critical frequency, and to substantially improve the attenuation at high frequency.

The MGAS filter (fig. 2) is a vertical oscillator which uses a crown of radially compressed curved blades to provide the mechanical compliance. The blades are clamped on one end to a plate, and connected on the other end to a small disk. The load connected to the disk compresses and bends the blades. Each MGAS filter houses 8 blades, and depending on their width, they can carry 10 to 30 kg. Acting on the position of the clamps one can change the blades' compression, and tune the MGAS resonant frequency down to 100 mHz. A device equivalent to the IP counterweight (not shown in the figure), called "magic wand", can be used to tune the effective MGAS COP [9], further improving the vertical filter attenuation for frequencies above a few Hz.

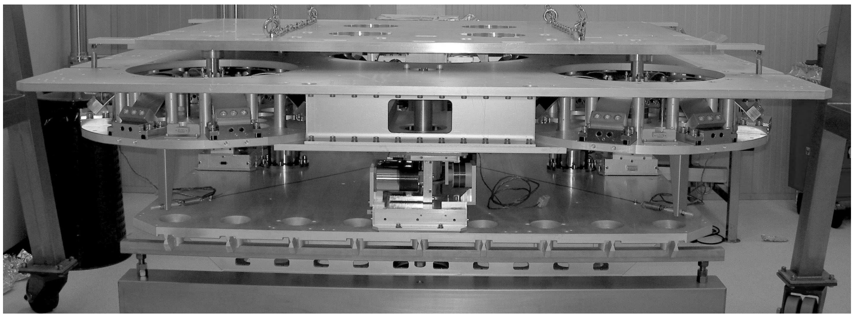

Figure 2. Upper picture shows the HAM-SAS prototype. Lower picture shows an MGAS filter before assembly.

Four IP legs arranged in a 1.1 m x 0.9 m diamond configuration (see fig. 1) are secured to a base through their flex joints. Four MGAS filters mounted on an intermediate 1.9 m x 1.7 m rectangular platform (spring box) supported by the IP legs, hold the optical table.The estimated payload (optical table plus optics and optic suspensions) is approximately 1000 kg. Each of the four MGAS filters and each of the IP legs are equipped with nanometric resolution LVDT position sensors and colocated voice-coil actuators which are used for automatic controls.

In order to increase the angular stiffness of the optical table, we introduced a temporary pitch/roll stabilizing device (see fig. 1). Such a device is constituted by a vertical shaft connected to one end to the plate supporting the optical table and to the other end to four helicoidal springs disposed in a cross configuration and attached to the spring box. The four springs hook to four wires and four tuning screws to reach the spring box corners and allow fine tilt tuning.

3. Seismic Attenuation Performance

We measured the passive attenuation performance using inertial sensors placed on ground and on the optical table as schematically shown in fig. 1. Signals from the sensors appropriately combined to obtain the seismic noise power spectral densities (PSDs) of all the six DOF are shown in figure 3. Blue curves are the ground spectra, and green curves are the optical table spectra. The high-frequency attenuation of the horizontal DOFs is more than 70dB. Attenuation in the frequency range from 15Hz to 40Hz is spoiled because of the pitch and roll resonances of the temporary stabilizing device. Resonances below 500 mHz are the undamped rigid body modes of SAS. The coarse leveling of the the spring box is probably responsible for the coupling among the DOFs.

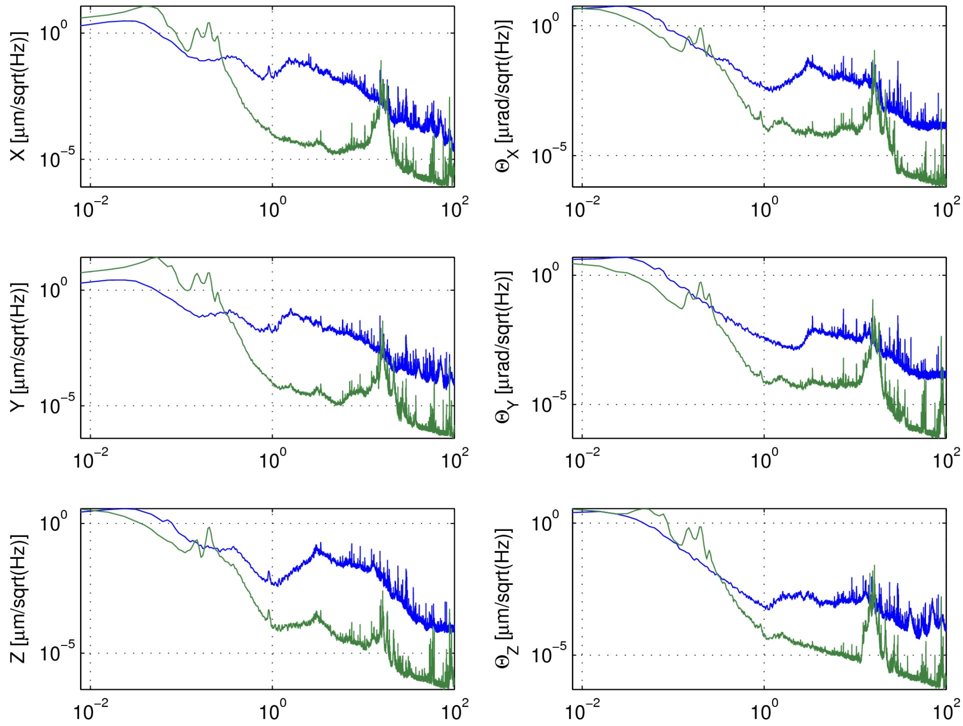

Figure 3. Comparison of seismic noise spectral densities of ground and of the passively attenuated optical table. Peaks below 500 mHz raising above the ground noise almost everywhere are the undamped rigid body modes. Resonances between 15 Hz and 40 Hz are due to the pitch and roll temporary stabilizing device. Above 60 Hz, the attenuated seismic noise measurement is limited by the sensors' noise placed on board of the optical table.

4. Control Strategies

HAM-SAS has been designed as a passive attenuation system for the gravitational wave sensitivy band. Automatic controls are therefore used only to maintain and change the position of the optical table, and damp the rigid body modes.

The control strategy that has been partially implemented during the prototype testing at LASTI is:

- tune all the rigid body modes close to the unstable equilibrium position at frequency below 80 mHz or even lower. This task can be done either mechanically tuning the oscillators, or using the control system and the electromagnetic antispring technique (EMAS) [10] to electronically tune the resonaces,
- apply a very low frequency position control relative to ground to maintain the system to a stable equilibrium position,
- damp the very low frequency modes respect to ground.

The advantage of this approach is that the system resonances are naturally damped using very low control forces, thus minimizing the rms seismic noise and maximizing the passive attenuation. Because of time constraints, we could not implement the first bullet of the control strategy, and we partially studied the EMAS control.

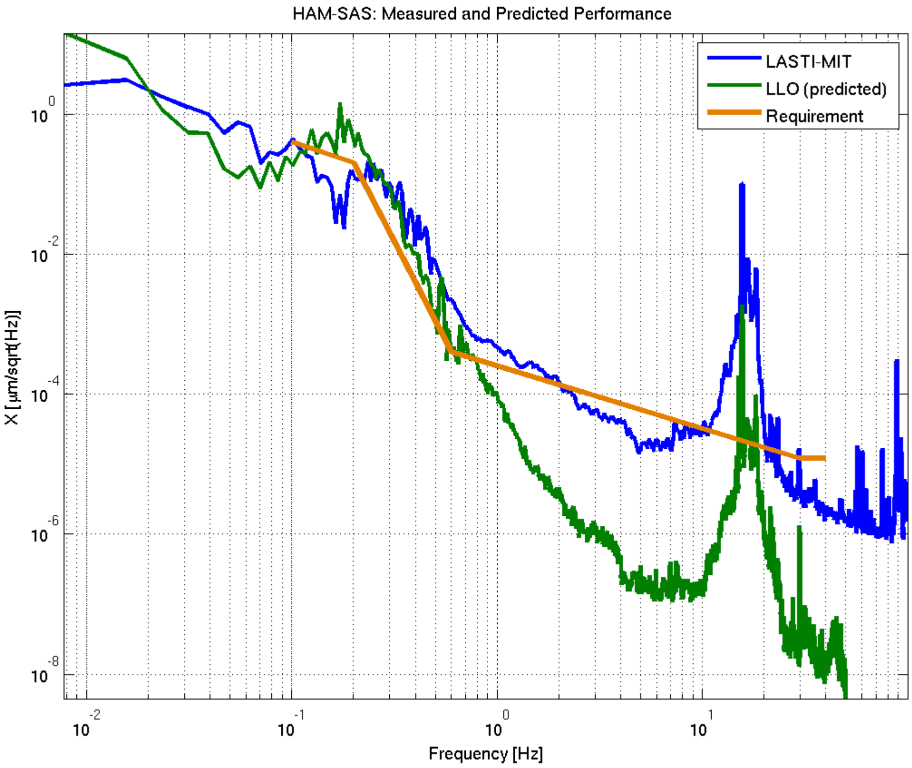

Figure 4. LASTI and Livingston filtered seismic noise power spectral densities(PSDs) of horizontal DOF x. Blue curve is the optical table motion PSD obtained at the LIGO LASTI MIT facility using a DC control, green curve is the predicted PSD obtained using Livingston site ground noise spectrum, gold curve is the AdLIGO HAM requirement.

The blue curve of figure 4 shows the results obtained for one horizontal degree of freedom x, using a DC control with unitary gain frequency (UGF) of approximately 100 mHz. To damp the vertical modes we set their control loops UGF at about 300mHz. The green curve shows the predicted motion PSD obtained using the ground noise spectrum of Livingston, LA, the noisiest LIGO site. The measured and the predicted performance are compared with the AdLIGO HAM seismic isolation requirements.

5. Possible Future Improvements and Conclusions

Even though actual performance does not completely meet the requirements, simulations show that the following modification will allow SAS to fulfill the AdLIGO isolation requirement:

- modification or retrofit of the stabilizing pitch/roll device. At least two possible solutions can be implemented. One simple solution is to damp the modes introduced by the stabilizing device using dissipative mechanical dampers. Recent measurements have shown that, using a simple elastic-polymer damper, the resonances quality factor are reduced by a factor 100. An alternative solution is the redesign of the device as shown in the right side of figure 1 where the resonances are eliminated by replacing springs and wires with flex joints and rigid hollow structures analogous to those used in the IP legs,

- mechanical tuning of all the rigid body modes below 80mHz to a quasi-stable equilibrium condition. This would automatically self damp all the mechanical modes resonances, whose quality factor is proportional to ω^2,
- better tuning of the existing DC control scheme.

Improvements that can further increase SAS performance:

- Transmissibility saturation reduction implementing the magic wands and the IP counterweights. An extra attenuation of 10dB-20dB is expected. This implementation would bring the SAS performance in line with the more stringent requirements for the BSC vacuum chambers.
- Use either the already present L4C geophones in feedback, or feeding forward to the table actuators an appropriate fraction of the force applied to the payload mirrors, to counteract the table recoil from the suspended optic swing during lock acquisition.

Acknowledgments

The LIGO Observatories were constructed by the California Institute of Technology and Massachusetts Institute of Technology with funding from the National Science Foundation under cooperative agreement PHY 9210038. The LIGO Laboratory operates under cooperative agreement PHY-0107417. The authors gratefully acknowledge the support of Ing. Carlo Galli and Dr. Chiara Vanni of Galli & Morelli s.r.l. during HAM-SAS fabrication phase.

This document has been assigned a LIGO DCC number LIGO-P070127-00-Z.

References

[1] Advanced LIGO Team, "Advanced LIGO Reference Design", LIGO Project internal note, LIGO-060056-08-M, (2006).

[2] Bertolini A, DeSalvo R, Galli C, Gennaro G, Mantovani M, Márka S, Sannibale V, Takamori A, and Torrie C, "Design and prototype tests of a seismic attenuation system for the advanced-LIGO output mode cleaner", *Class. Quantum Grav.*, 23:S111–118, 2006

[3] Takamori A, Raffai P, Márka S, DeSalvo R, Sannibale V, Tariq H, Bertolini A, Cella G, Viboud N, Numata K, Takahashi R, Fukushima M, "Inverted pendulum as low frequency pre-isolation for advanced gravitational wave detectors". Accepted by *Nucl. Instrum. Meth. A* , 2007.

[4] Losurdo G. et al., "An inverted pendulum preisolator stage for the VIRGO suspension system", *Rev. Sci. Instrum.,* **70** (1999) 2507-2515-

[5] Cella G, DeSalvo R, Sannibale V, Tariq H, Viboud N, Takamori A, "Seismic attenuation performance of the first prototype of a geometric anti-spring filter", *Nucl. Instrum. Meth. A,* **487** (2002) 652-660

[6] Cella G, Sannibale V, DeSalvo R, Márka S, Takamori A, "Monolithic geometric anti-spring blades", *Nucl. Instrum. Meth. A*, **540** (2005) 502-519

[7] Sannibale V, Bertolini A, Cella G, DeSalvo R, Márka S, Numata K, Stochino A, Takamori A, Tariq A, "A new seismic attenuation filter stage MGASF for advanced gravitational wave interferometric detectors", to be submitted to *Nucl. Instrum. Meth. A*

[8] Tariq H, Takamori A, Vetrano F, Wanga C, Bertolini A, Calamai G, DeSalvo G, Gennai A, Holloway L, Losurdo G, Márka S, Mazzoni M, Paoletti F, Passuello D, Sannibale V and Stanga R, "The linear variable differential transformer (LVDT) position sensor for gravitational wave interferometer low-frequency controls", *Nucl. Instrum. Meth. A,* **489** (2002) 570-576

[9] Stochino A, DeSalvo R, Huang Y and Sannibale V, "Improvement of the seismic noise attenuation performance of the Monolithic Geometric Anti-Spring filters for gravitational wave interferometric detectors", *Nucl. Instrum. Meth. A*, **580** (2007) 1559-1564

[10] Mantovani M, DeSalvo R, "One hertz seismic attenuation for low frequency gravitational waves interferometers", *Nucl. Instrum. Meth. A,* **554** (2005) 546-554