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

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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 damp rigid body modes. 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 promises 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 of 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 required design sensitivity.

2. HAM-SAS

The HAM-SAS (fig. 1) 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 the optical benches of the so called Horizontal Access Module vacuum chamber (HAM) of the future Advanced LIGO interferometers.

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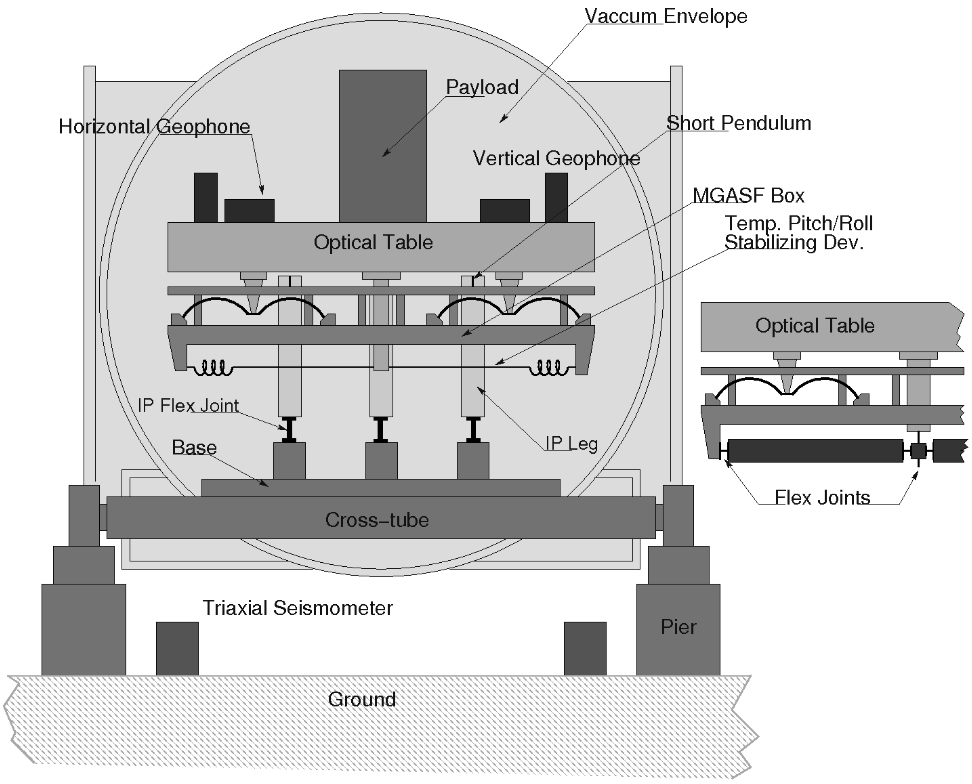

Figure 1. Sketch of HAM-SAS mechanical system, and the improved pitch/roll stabilizing device of the optical table. Black bold lines indicate elastic structures, same color filled parts indicate rigid structures.

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) [5, 6, 7] for the vertical DOFs. Both devices exploit the fundamental property that the response of a harmonic oscillator to seismic excitation is equivalent to a second-order low pass filter. Since a real mechanical oscillator always has 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 simply increasing the IP payload. A counterweight placed below the IP pivot point allows to tune the center of percussion (COP) of the system [3, 4]. Such a tuning allows to increase the saturation critical frequency, and therefore 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 thickness, each blade they can carry up to 38 kg. The blades stress is kept down to 40% - 60% of the yield point [7]. 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 [8], further improving the vertical filter attenuation for frequencies above a few Hz.

Four IP legs with coarsely tuned counterweights, arranged in a 1.1 m x 0.9 m diamond

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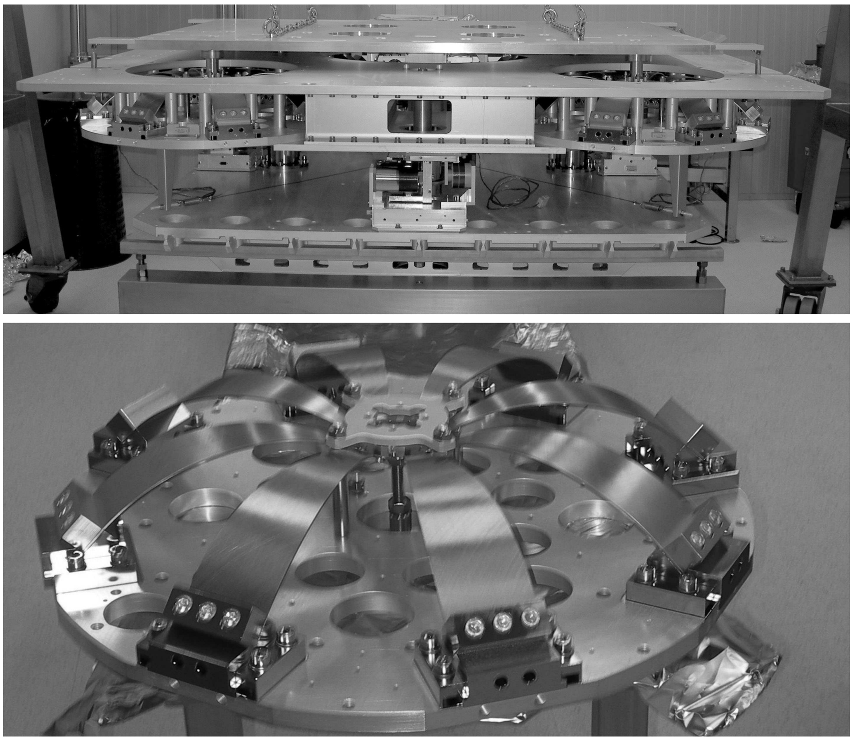

Figure 2. The upper picture shows the HAM-SAS prototype. The lower picture shows a MGAS filter before assembly.

configuration (see fig. 1) are secured to a base through their flex joints. Four MGAS[1] filters with no magic-wands 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 [9] and co-located voice-coil actuators which are used for automatic controls.

In order to increase the angular stiffness of the optical table, we introduced a pitch/roll stabilizing device (see fig. 1). Such a device comprises a vertical shaft, four helicoidal springs, and four wires. The shaft is connected to one end to the plate supporting the optical table. The other end holds the helicoidal springs each one attached to the spring box corners through a wire. Four screws, each one placed between a wire and a corner, allow the fine tuning of pitch and roll DOFs.

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. Black curves are the ground spectra, and gray 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 coil spring resonances in the

[1] Even though the filters used in HAM-SAS have the blades tips bolted to the central disk, they are described by the same dynamics of a monolithic blade filter.

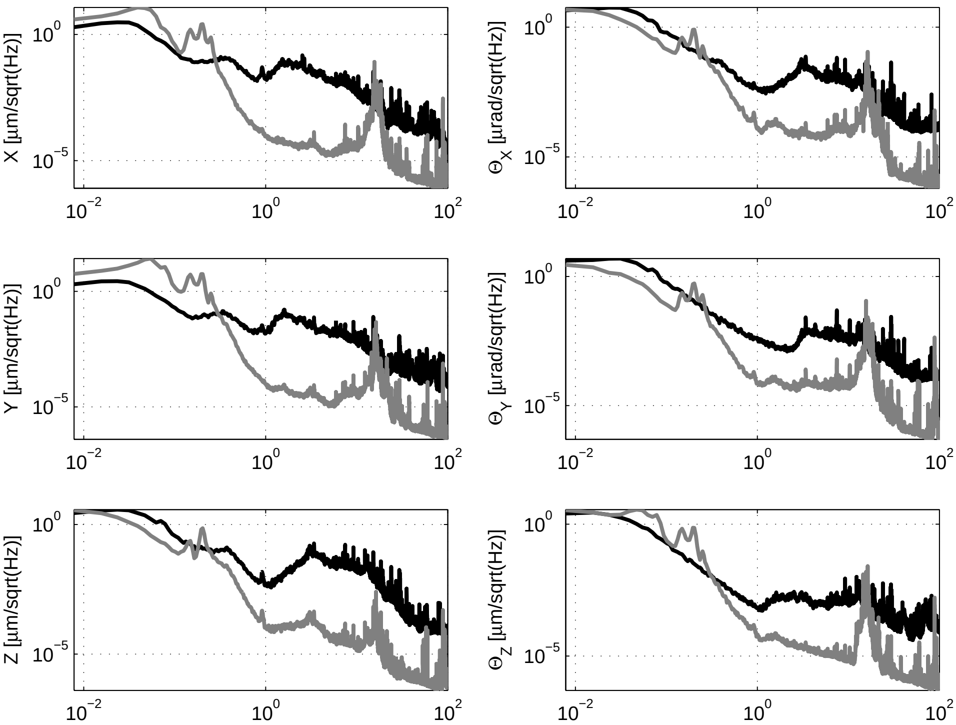

Figure 3. Comparison of seismic noise spectral densities of ground (black) and of the passively attenuated optical table (gray). Peaks below 500 mHz raising above the ground noise almost everywhere are the undamped rigid body modes. Resonances between 15 Hz and 40 Hz are due to the pitch and roll stabilizing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

vertical angle stabilization system. 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.

4. Control Strategies

The HAM-SAS has been designed as a passive attenuation system for the gravitational wave sensitivity 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 a frequency below 80 mHz or even lower. This task can be done either by mechanically tuning the oscillators, or using the control system and the electromagnetic anti-spring technique (EMAS) [10] to electronically tune the resonances,
- apply a very low frequency position control relative to ground to maintain the system at a stable equilibrium position,
- damp the very low frequency modes with respect to the ground.

The advantage of this approach is that the system resonances are naturally damped [11] using very low control forces, thus minimizing the rms seismic noise and maximizing the passive

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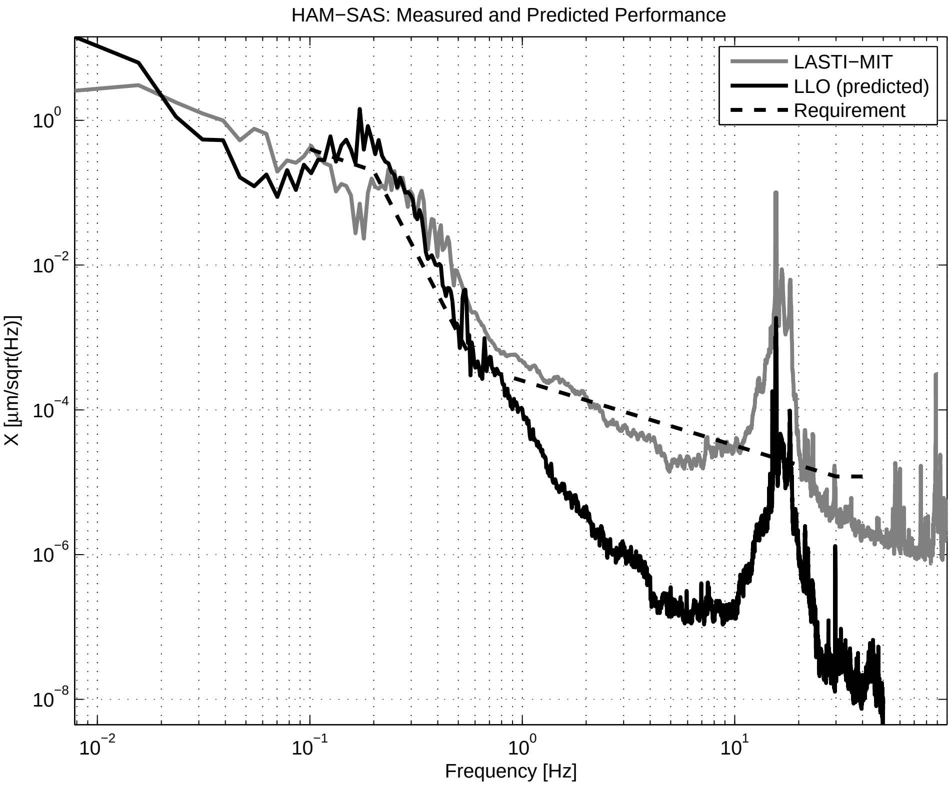

Figure 4. LASTI and Livingston filtered seismic noise power spectral densities (PSDs) of horizontal DOF x. The gray curve is the optical table motion PSD obtained at the LIGO LASTI MIT facility using a DC control, the black curve is the predicted PSD obtained using Livingston site ground noise spectrum,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

attenuation. Because of time constraints, we could not implement the first bullet of the control strategy, and we only partially studied the EMAS control.

The gray curve of figure 4 shows the results obtained for one horizontal degree of freedom (DOF), 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 black 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 the actual performance does not completely meet the requirements, simulations indicate that the following modification would 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 introducing the magic wand device and properly tuning the IP counterweights. An extra attenuation factor of 10dB-20dB is expected.
- 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 optics swing during lock acquisition.

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