Design and prototype tests of a Seismic Attenuation System for the Ad-LIGO Output Mode Cleaner

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Abstract. Both present LIGO and Advanced LIGO will need an Output Mode Cleaner (OMC) to reach the desired sensitivity. We designed a suitable OMC seismically attenuated optical table fitting into the existing vacuum chambers (HAM chambers). The most straightforward and cost effective solution satisfying the Ad-LIGO seismic attenuation specifications was to implement a single passive seismic attenuation stage, derived from the SAS concept. We built and tested prototypes of all critical components. Based on these tests and past experience, we expect that the passive attenuation performance of this new design, called HAM-SAS, will match all requirements for the LIGO OMC, and all Ad-LIGO optical tables. Its performance can be improved, if necessary, by implementation of a simple active attenuation loop at marginal additional cost. The design can be easily modified to equip the LIGO BSC chambers and leaves space for extensive performance upgrades for future evolutions of Ad-LIGO. Design parameters and prototype test results are presented

1. Introduction

The LIGO interferometers[1] need an Output Mode Cleaner in order to increase the power stored in their beams and reduce the shot noise limit. Advanced LIGO has similar and even more compelling reasons to implement an OMC[2]. Despite the present financial constraints, LIGO has been exploring the possibility of an early implementation of an OMC. It is natural to require that the seismic attenuation of the OMC optical bench for present LIGO be easily modified for use in forthcoming Ad-LIGO. Moreover the design should be as simple and inexpensive as possible while satisfying the Ad-LIGO seismic attenuation specifications.

We designed a single stage, passive attenuation unit[3] based on the SAS technology[4]. It can satisfy practically all Ad-LIGO seismic attenuation specifications and has built-in nanometric precision positioning, tide-tracking and pointing instrumentation. Its sensors and actuators are designed to allow inexpensive upgrade to active attenuation. This upgrade would require installation of a set of accelerometers and control logic and would add to the passive performance thus substantially exceeding the requirements. Since in HAM-SAS the horizontal and vertical degrees of freedom are mechanically separated and orthogonal, it is expected that its active control loops would be simpler and easier to maintain than one of the six degree of freedom control stages of the present baseline active attenuation scheme.

Additionally HAM-SAS would bring to LIGO earthquake protection for seismic excursions as large as ± 1 cm.

HAM-SAS is designed to be implemented completely inside the present ultra High Vacuum HAM chambers, replacing the present LIGO seismic attenuation stacks below the present optical benches. Consisting of a single attenuation layer, and not requiring the replacement of the optical benches, it is expected to cost less than a third of the present, baseline Ad-LIGO, three-stage active attenuation system[5,6], while delivering better attenuation performance with a fraction of its complexity and a negligible amount of under-vacuum power dissipation.

An additional, not-easily-quantifiable, advantage of HAM-SAS is that its technology is homologous to the multiple pendulum suspensions that it supports, thus forming a more homogeneous and easier to handle seismic attenuation and mirror suspension system.

HAM-SAS can be scaled up to isolate the heavier BSC optical benches. The BSC chamber configuration would require the suspension of the BSC optical bench from four wires, thus introducing a bonus stage of horizontal attenuation.

Unlike the baseline Ad-LIGO active system HAM- (or BSC-) SAS do not require instrumentation on the piers. If future upgrades of Adv-LIGO were requiring additional seismic attenuation this space would remain available. The HAM-SAS attenuation performance could be augmented with the addition of an already designed external stage[7], without introducing any additional in-vacuum instrumentation.

HAM-SAS is composed of three parts:

- A set of four Inverted Pendula (IP) for horizontal attenuation
- A set of four GAS springs[8,9] for vertical attenuation
- A set of eight nm resolution LVDT position sensors and non-contacting actuators for positioning and pointing of the optical bench. Micropositioning springs ensure the static alignment of the optical table to micrometric precision even in case of power loss.

A view of a complete HAM-SAS system is shown in figure 1, please consult the construction drawings for more detail.

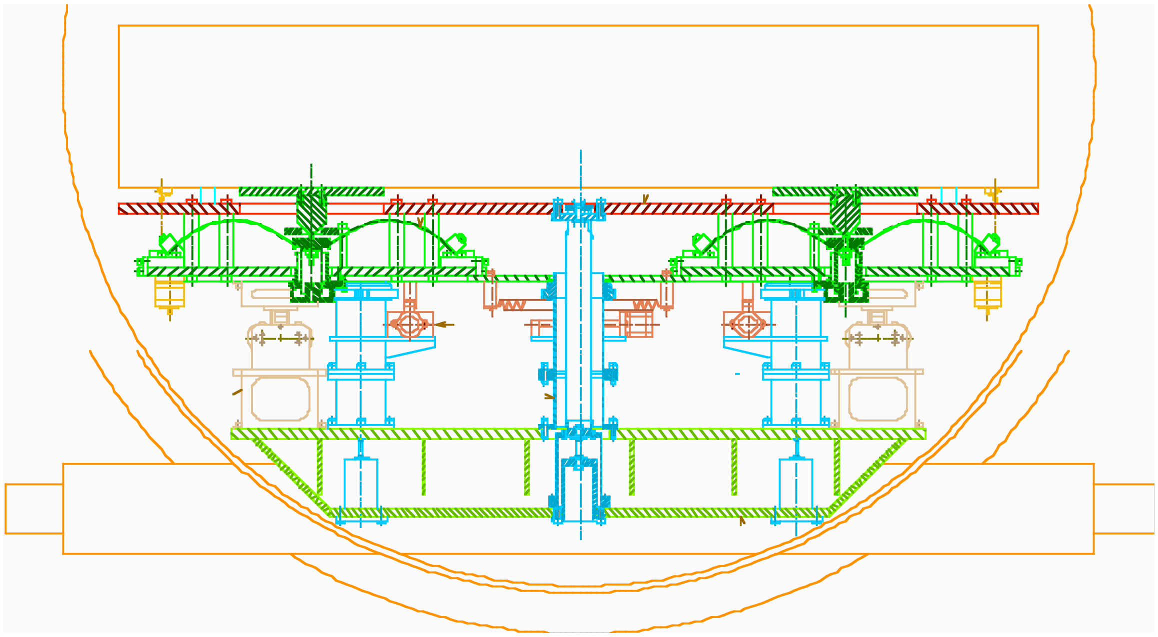

Figure 1: The existing optical bench (large orange rectangle) is supported by a spring-box composed by two aluminum plates (red and green plates below the bench). The GAS springs (green arches) support the bench on a modified kinematical mount; each is provided with coaxial LVDT position sensors and voice coil actuators, and parasitic, micrometrically tuned, springs to control vertical positioning and tilts. The spring box is mounted on IP legs (blue) that provide the horizontal isolation and compliance. The movements of the spring-box are also controlled by four groups of co-located LVDT position sensors, voice coil actuators and parasitic springs (brown). The IP legs bolt on a rigid platform (green) which rests on the existing horizontal cross beam tubes (orange). Part of the existing vacuum chamber envelope is also shown in orange.

2. Horizontal attenuation, the Inverted Pendula (IP)

IPs are horizontal-movement mechanical oscillators commonly used for their good attenuation properties. They can be tuned to resonant frequencies to tens of mHz by adjusting their payload with ballast masses. Tuning IP below 10 mHz should be possible with electromagnetic parasitic springs, recently tested on vertical attenuation filters[10]. The IP attenuation performance is only limited by the effects of the momentum of inertia of its legs. When the seismic motion shakes the bottom of the leg, the top of the leg (where the payload is attached) counter-shakes and transmits part of the seismic motion to the payload. The amount of transmitted movement is proportional to the ratio of the legs' weight over the payload mass times a geometrical factor. To neutralize this effect, counterweights are attached to the legs below their lower flex joint.

With taller legs[11-13] attenuation factors in excess of 60 dB are obtained with counterweights. For small legs like the ones required by HAM-SAS (or BSC-SAS) more than 60 dB can be obtained without counterweights and more than 80 dB with counterweights.

A small prototype IP table was fabricated to validate the attenuation performance of the HAM-SAS IP legs. Although full-size legs were used, we built only a three leg, 12% load (105 Kg) prototype to allow tests on an existing, limited capacity, test facility at Galli & Morelli. The measured transfer function, figure 2, showed the expected dip at the end of the attenuation roll off, followed by the 60 dB saturation level induced by the leg's momentum of inertia.

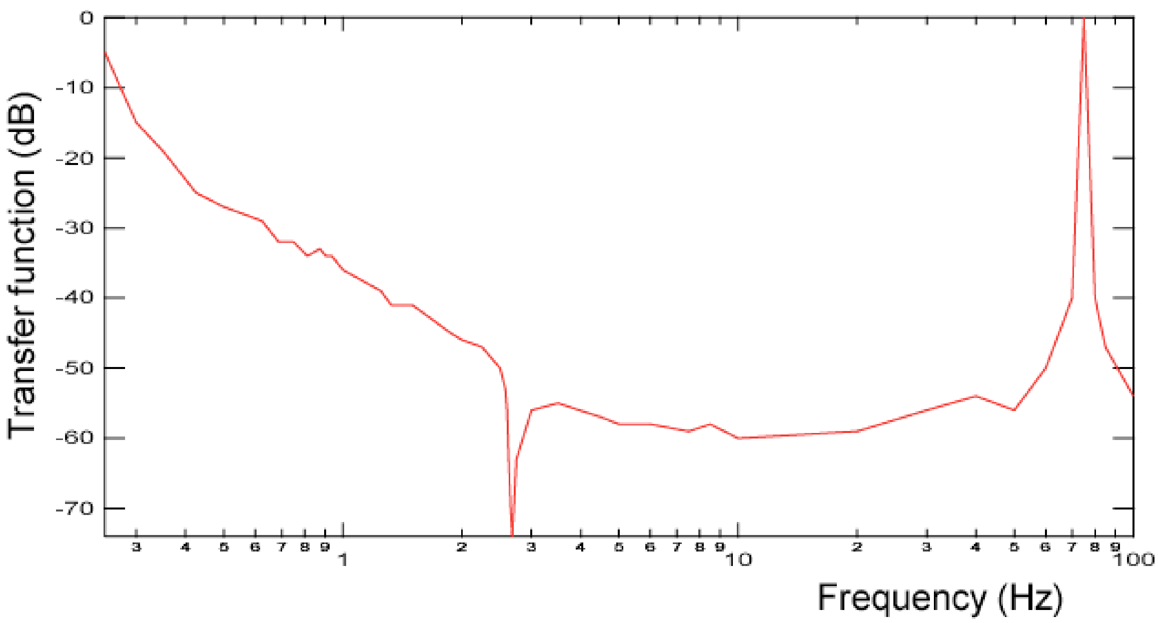

Figure 2: Mechanical transfer function of a HAM-SAS IP table. Full size legs with reduced load (thinner flex joint) were tested in this measurement.

The leg's attenuation properties are expected to improve by an additional 18 dB at full load. At 80 Hz the sharp leg-flex joint resonance was observed.

Tests with full size flex joints and payload (750 kg on 3 legs) were attempted but, due to test facility limitations, they only showed attenuation in excess of 60 dB, with no quantitative measurement of the saturation level. Also, with the stiffer flexures, the 80 Hz resonance moved to over 100 Hz. The resonance quality factor was reduced (its time constant went from 4.3 s to 35 ms) by mounting simple, passive, magnetic dampers around the legs' top flex joints, a location at which this mode generates large translations and around which, for the table translation, the leg rotates and does not translate. Therefore the magnetic braking is quite effective to damp the unwanted mode without affecting the attenuation performance.

The introduction of counterweights would improve the IP passive attenuation performance well beyond 80 dB. There is no space in the HAM vacuum chambers to mount counterweights on all four HAM-SAS legs in the Ad-LIGO configuration. We found that double counterweights can be mounted on the two axial legs, and we calculated that they will give the same attenuation performances than standard counterweights on all legs. We therefore expect to achieve better than 80 dB passive horizontal attenuation from the HAM-SAS. As for frequency tuning, the loading curve of the full load IP prototype measured, It was not tuned below 60 mHz because of instabilities of the lab floor (red points in figure 3). Tuning below 50 mHz is possible with ballast block no smaller than 1 Kg (blue points in figure) on a more solid ground. Attenuation in excess of 60 dB can be expected starting at 1

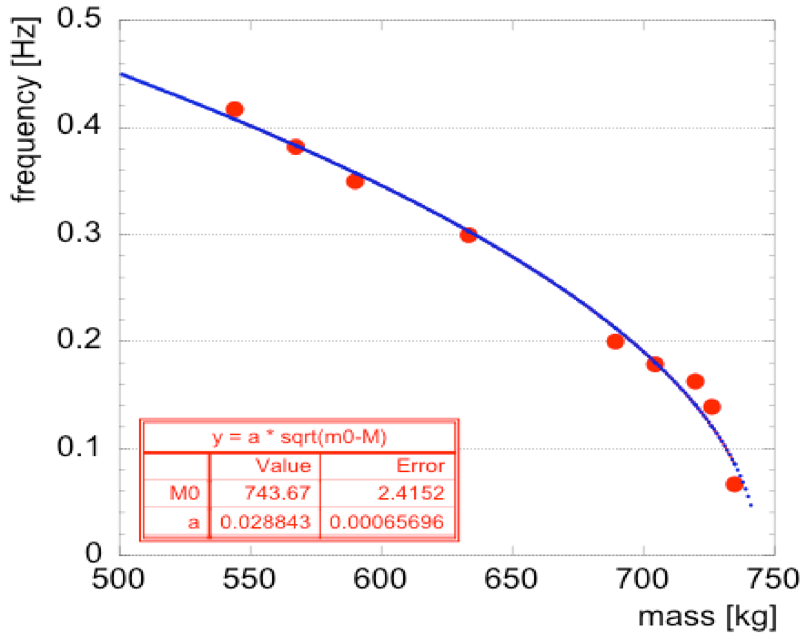

Figure3: Frequency versus load measurement of the full payload IP prototype.

Hz on a setup bolted to the floor. Lower frequency performance can be obtained with e.m. spring tuning.

The objection was posed that it is not possible to build a table sitting stably over four legs. The objection is true only if the table platform, in this case the vertical attenuation spring box, is stiffer against warping than the longitudinal elasticity of the legs. The problem does not subsist because the platform is designed to be flexible during assembly. It becomes rigid only when the bolts between its two separate surfaces are tightened. This operation is performed after the spring box has properly settled on the four legs and then it conserves its proper mechanical stability over the 4 legs.

3. Vertical attenuation, the Geometric Anti Springs (GAS)

Vertical attenuation is obtained using a stage with four GAS filters with blades' shape identical to the ones used in the TAMA-SAS top filters[13]. Eight blades per filter, instead of three are used to handle the larger payload.

An attenuation saturation level of 60 dB has been verified for these filters. Their resonant frequency was tuned down to 30 mHz in air, using only analog electronics[10]. Tuning at even lower frequencies may be possible in vacuum and with digital electronics.

The HAM Optical table would sit on top of the four GAS filter using a modified kinematics mount (a GAS filter supporting and positioning the table with a sphere in a cone, the opposite filter defining the rotation angle with a sphere in a groove, and the two cross filters supporting the balance of the weight with spheres on flats).

4. Positioning and pointing, LVDT position sensors and voice coil actuators

In HAM-SAS the spring box only moves in the horizontal plane (x-y and yaw) while the optical bench only moves in the remaining three degrees of freedom (z, pitch and roll) with respect with the spring box. The 6 by 6 positioning and control matrix then naturally and conveniently splits into two independent three-degree-of-freedom matrices. Sensors and actuators are co-located to roughly diagonalize the controls within each of the three degree of freedom matrices.

Instrumentation for sensing and actuation is applied in groups of four, even if each system has only three degrees of freedom. This arrangement was chosen because of the rectangular symmetry of the vacuum chamber feed-throughs and of the optical bench. Four instruments for three degrees of freedom are a redundant system, one of the instruments can be ignored, or three diagonalized virtual sensors can be synthesized from the four actual ones.

The function of the LVDT position sensors is to determine the positioning and orientation of the optical bench. The initial development of these sensors achieved a position resolution of 20 nm[14]. Their electronics performance has since been improved bringing their resolution down to 1 nm, over a stroke of 10 mm. This resolution likely exceeds the stability of the floor and is deemed sufficient to satisfy the Ad-LIGO specs. Another important function of the LVDTs is to provide the position memory needed to bring back the table in the original alignment after interventions on the optics.

The horizontal direction dynamic actuators are specially-designed, non-contacting, "racetrack" voice coils[15] delivering constant force within better than a percent over a field of movements of 10 mm in diameter in the horizontal plane. They deliver force sufficient to deal with tidal movements and thermal excursions of 1^{o}K with less than a mW of maximum power dissipation. They are capable to position the table within the resolution of the LVDT position sensors.

If need be, these actuators are capable of high frequency operation for complementary active attenuation.

The vertical direction dynamic actuators are similar performance, but more traditional design, non-contacting voice coils.

Micrometrically and remotely controlled parasitic springs are used to null the static current of the dynamic actuators. This solution has multiple advantages. It maintains alignment within a few microns even in the event of complete power loss, it makes in-vacuum power consumption practically negligible, and, by reducing the force requirements on the actuators to mN levels, it minimize their actuation noise.

5. Attenuation performance reserve, complementary active attenuation

Active attenuation can be implemented to complement the HAM-SAS passive attenuation performance. The structure is particularly favorable to active attenuation for several reasons.

- the system is composed of rigid platforms suspended on soft springs and actuated by weak actuators. The possibility of actually warping the structure with the actuators or exciting their warp modes is thus virtually eliminated.
- the control power requirements, which grow with the fourth power of the suspension frequency, are strongly reduced, depressing the actuation noise.
- the two 3 d.o.f. controls are much easier to handle than a 6 d.o.f. problem.
- having to deal with only the horizontal d.o.f. in the first stage allows the use of custom designed horizontal accelerometers, strongly insensitive to vertical excitation ($<10^{-4}$). The injection of vertical movement noise into the horizontal control forces is thus strongly reduced. The vertical accelerometers, more difficult to shield against horizontal noise, operate in an already horizontally quiet environment and are therefore less sensitive to noise cross injection between orthogonal d.o.f..

The HAM-SAS dynamic actuators are perfectly adequate for active attenuation. To implement active attenuation it is therefore only necessary to implement suitable accelerometers and external control electronics. The HAM-SAS design is pre-engineered for this case.

6. Switching to Ad-LIGO

All HAM-SAS components has been designed on 115 mm tall shims. In order to reconfigure from LIGO-I to Ad-LIGO it is sufficient to eliminate the shims and change, where necessary, the flex joints and GAS filter blades to match the different payloads.

7. Vacuum compatibility and applicability to the BSC chambers

The HAM-SAS design was made using only LIGO pre-approved materials and trapped volumes venting design practices. Additionally it is designed for creep-relieving bakeout cycles, which are more stringent than UHV baking requirements.

The BSC chambers have hang-down and heavier optical benches. There is no problem in resizing flex joints and GAS blades to match all Ad-LIGO weight requirements with a lot of spare capacity. Because of the hang-down geometry it is not possible to reuse the present BSC optical benches, new ones would be necessary. Also the optical bench of the BSC is almost half a meter below the level where one would position a BSC-SAS spring box. The optical bench would then be suspended from the four GAS filters using double-nail-head wires as in the well tested Virgo injection and detection benches. This will provide a bonus of 40 dB of horizontal attenuation above 5 Hz. Positioning and pointing control would be done with the same LVDT and non-contacting actuators. An additional set of three sensor and actuators may be needed if a direct and finer control of the suspended optical bench is desired.

8. Further upgradeability, external low frequency preisolators

HAM-SAS (and BSC-SAS) have no need of external pre-isolation to match the Ad-LIGO seismic attenuation specifications. However future upgrades may require increases of seismic attenuation performances. An external SAS, on-pier, pre-attenuator design was prepared years ago to solve the Livingston falling tree problem while waiting for the HEPI development. That design can be implemented upstream of HAM-SAS or BSC-SAS without breaking the vacuum and providing a minimum of 40 dB of supplemental seismic attenuation in all degrees of freedom.

9. Conclusions

We designed a simple, low cost, high performance seismic attenuation system capable to satisfy all present LIGO output mode cleaner and all Ad-LIGO requirements, while leaving space for substantial performance upgrades in case future Ad-LIGO evolutions were to require an even quieter environment.

All critical components were successfully tested and showed more than satisfactory performance. The design is ready for production and implementation in LIGO.

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References

[1] B. Abbott, et al., “Detector description and performance of the first coincidence observations between LIGO and GEO”, Nuclear Instruments and Methods in Physics Research A 517, p. 154-179. (2004)

[2] LIGO document T010075-00-D

[3] LIGO document D050100-00-D to D050150-00-D complete design set

[4] R. DeSalvo, “Passive, Non-linear, mechanical structures for seismic attenuation” Fifth ASME International Conference on Multibody Systems, Nonlinear Dynamics and Controls, September 24-28, 2005 – Long Beach, California, USA, and references therein, LIGO-P050001-00-D

[5] N. Robertson, et al., Proceedings of SPIE, vol 5500 (2004), p 81-91

[6] R. Abbott, et al., “Seismic Isolation enhancement for initial Advanced LIGO”, CQG21, (2004), S915-S921

[7] LIGO document D020001-00-R and T040197-00-R.

[8] G. Cella, V. Sannibale, R. DeSalvo, S Marka, A Takamori, “Monolithic geometric anti-spring

blades" Nuclear Instruments and Methods in Physics Research Secttion A, 540 (2005) 502-519

[9] G. Cella, R. DeSalvo et al. "Seismic attenuation performance of the first prototype of a geometric anti-spring filter" Nuclear Instruments and Methods in Physics Research A 487, Issue 3, p. 652-660. (2002)

[10] M. Mantovani, R. DeSalvo, "One Hertz Seismic Attenuation for Low Frequency Gravitational Waves Interferometers", accepted for publication on Nucl. Instr. and Meth. (2005),

[11] G. Losurdo, et al., Rev. Sci. Instr. 70, (1999), p 2507

[12] G. Losurdo, et al., Rev. Sci. Instr. 72, (2001), p 3653

[13] Ryutaro Takahashi, this conference

[14] H. Tariq, et al. "The Linear Variable Differential Transformer (LVDT) Position Sensor for Gravitational Wave Interferometer Low-frequency Controls" Nuclear Instruments and Methods in Physics Research Section A, Volume 489, Issue 1-3, p. 570-576.

[15] C. Wang, et al., "Constant force actuator for gravitational wave detectors seismic attenuation systems." Nuclear Instruments and Methods in Physics Research Section A, Volume 489, Issue 1-3, p.563-569