LASER INTERFEROMETER
GRAVITATIONAL WAVE OBSERVATORY
- LIGO –
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Applying the SAS Know-How to produce remedial solutions to the LIGO seismic isolation shortfall at Livingston
1: Active Internal Stack Damping

Alessandro Bertolini, Riccardo DeSalvo, Francesco Fidecaro, Szabolcz Marka,
Luca Matone, Virginio Sannibale, Duccio Simonetti, Akiteru Takamori, Hareem Tariq

California Institute of Technology
LIGO Laboratory - MS 18-34
Pasadena CA 91125
Phone (626) 395-212
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Laboratory - MS 16NW-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

www: http://www.ligo.caltech.edu/

Introduction

Due to intermittent seismic activity (mainly of cultural origin) between 1 and 3 Hz[1] the LLO interferometer during daytime cannot achieve or maintain lock for long periods. The reason is that occasional seismic bursts, with velocities up to 5 μm/sec in the 1-3 Hz frequency band, excite resonant modes of the stacks to the point of overwhelming the mirror control authority. Therefore an urgent remedial action is needed[2].

The SAS group has looked into the possibility of using the SAS know how and capabilities for this remedial action. Two ideas have been considered.

The first idea is to use the existing LVDT sensors[3] and constant force actuators[4] sensing and acting across the entire attenuation stack and directly apply electronics viscous damping to reduce the quality factor of the stack resonances in the critical frequency band. Viscous damping of an optical bench to the required level over all six degrees of freedom has already been achieved [5]. The danger intrinsic with this idea is that the actuation is made downstream of the attenuation and therefore any actuation noise at higher frequency is re-injected directly to the mirror suspension point. The scheme heavily relies on the high performance of the constant force actuator and on the feasibility or rolling off sufficiently rapidly the actuator noise above 3 Hz leaving enough phase margin for a robust control.

As a bonus, during the installation of the hardware of the active damping option, it will be possible to install accelerometers on the optical bench to allow in the future active isolation through inertial damping.

This solution can be regarded as quite intrusive because it requires installation of hardware inside the vacuum envelope and may disturb the interferometer alignment.

The second idea is to directly apply the proven and well-known SAS pre-attenuation technology on the four piers to passively negate the stacks' seismic excitation and install LVDTs, constant force actuators and accelerometers, also externally, to damp the residual stack excitation.

The first option was supported to the level of making a full design and building a prototype to be tested in LASTI and is reported here. The second option, so far, has only been carried forward as a theoretical study and is discussed in a separate paper[6].

Active Internal Damping Option

To solve the problem of the LIGO I stack resonances being excited by seismic activity one could think of simply following the successful Virgo strategy of sensing and counter-acting the attenuation chain's rigid body modes (the equivalent of the stack's modes) on the first attenuation step and let the following attenuation steps absorb any possible high frequency re-injected noise.

The practical problem in LIGO I is that the attenuation stacks are split in four independent columns just after the vacuum penetration bellows. Each column has its own independent, if somewhat degenerate, resonances. The four columns mechanically reconnect only at the optical bench level. The logical equivalent of the Virgo strategy would be to apply sensors and actuators on the first mass of all four stacks. Being each stack stage a six degree of freedom oscillator, this would entail sensing and actuating in 24 degrees of freedom. The complexity of this arrangement is regarded as prohibitive and geometrically it would be of difficult implementation.

The only practical option, and geometrically an easy task, is to sense and actuate between the platform that supports the four stacks and the optical bench.

The scheme is the one being developed and is illustrated in figures 5 to 8 for the BSC; a similar arrangement is possible also for the HAM chambers.

Damping the stack resonances is a comparatively easy task, we plan to demonstrate this in a HAM prototype assembled in the Caltech Synchrotron lab. We would then verify the concept on the BSC stacks during the system vacuum validation at LASTI.

The problem is that the proposed geometry violates our own (TAMA SAS and Virgo) basic tenet of isolation, which is to apply the active damping in the first step of a chain and rely on the next attenuation steps to filter out any possible actuation noise. The solution forced by the LIGO I geometry bridges and potentially can cross circuit all 4 (3 for HAM) stack stages of attenuation. This is clearly not something that we would have willfully designed.

Several possible noise re-injection routes have being identified and, on paper, cleared. Some possible routes have been evaluated and trivially eliminated. The most worrisome are listed below.

- The system relies heavily on the insensitivity to the position of the constant force actuator. Despite the very stringent requirements imposed by the attenuation performance of the SAS IP in TAMA the constant force actuators proved to be better than required in that single attenuation stage. This is not necessarily the case across the multiple step LIGO stacks.

To evaluate the re-injected noise across the stacks, let’s examine the actuator’s force requirements.

We approximate the stack as a 1 ton mass, 1 Hz oscillator, subject to a 1 μm seismic motion at 1 Hz. To neutralize a 1 μm seismic excitation we need 1 N peak force. The actuator configuration described in the first half of the actuator paper was delivering 1.2 N/A, the previous prototype was twice as strong and, if needed, more than one layer of copper can be spun on the coil, so the required force is easily achieved at low power levels.

To evaluate the re-injected noise due to seismic shaking of the instrument, it is useful to consider the average standing force applied. We assume that the required level of actuation would entail 500 mN of average standing force.

The actuator has been measured to produce a force constant to the tenth of the percent (measurement limited by the scale resolution) over 20 mm.

We assume here a force slope equal to the upper limit measured, i.e. 10^{-3} over 20 mm. We then subject this actuator to a high frequency seismic noise of 1 micron. This would produce a force modulation of

$F = 0.5\ \mathrm{N} * 10^{-3} * 10^{-6}\ \mathrm{m} / 2\ 10^{-2}\ \mathrm{m} = 25\ \mathrm{nN}.$

The critical question is how much movement would this noise generate to the 1 ton payload mass at 35 Hz. In doing this estimation we assume a seismic motion of 1 μm at 35 Hz, which is a large overestimate.

We estimate a peak displacement:

$$s = F / (8 \pi^2 f^2) M = 25 / (8 \pi^2 35^2) 1000 \text{ nm} = 0.26 \text{ fm at } 35 \text{ Hz.}$$

This estimated number turns out to be just right when compared with the requirements of 2.5 10^{-16} m/√Hz noise at the top of the 0.7Hz suspension pendulum to give the customary 10^{-19} m/√Hz noise at the test mass.

- Imperfections in coiling can give rise to magnetic field modulations that can generate significant up-conversion of the 1 to 5 Hz seismic displacement. Applying a coiling uniformity error of half a spire on one side of the peak field gradient of the permanent magnet induces, above 35 Hz, a smaller up-converted noise than the above limit.
- The actuator's confined but strong magnetic field may generate Eddy current damping in the coil. The ensuing 1/f transfer function would then bypass the $1/f^8$ stack performance. Viewing the actuator coil as a single spire, it is easy to realize that the geometry that produces the constant force performance also neutralizes the integrated magnetic field flux variations, consequently neutralizing the Eddy current problem.
- The most worrisome of these routes is the electronics noise being reintroduced in the actuator signal. This problem can be solved by steeply rolling off, with multiple low pass filters, the coil driver bandwidth above 3 Hz.

The difficult part is to roll off the electronics noise while leaving enough phase margin for a stable damping scheme. As it can be seen in figure 5 of the constant force actuator paper, at least four orders of magnitude have to be rolled off between 5 and 35 Hz to meet the specs. This appears to be feasible in a simplified model, but remains to be practically tested on the full system and six degrees of freedom at the Synchrotron lab prototype.

- The feed back signal of the damping actuators may apply direct force on the mirror's magnets but the actuators coils mounted above the optical bench and inside the boot should be well shielded. Rolling off the actuator signal above 3 Hz will also reduce the possibility of this direct electromagnetic actuation on the mirror's magnets.

The real problem will be to validate the noise estimations. In the real LIGO interferometer it will be trivial to verify whether the proposed active damping system will re-inject any significant noise, by simply switching the controls on and off in a period of quiet seismic activity. At LASTI, it may be difficult to prove that no significant noise (at the level of 10^{-16} m/√Hz) is re-injected on the optical bench. Consequently, we may have to take the risk of installing the active damping system in LLO and only then verify the actual amount of re-injected noise.

The noise re-injection is a non negligible, and possibly lethal risk. Fortunately the interferometer locking is affected by short seismic activity bursts only 100 times per day or so. If the re-injected noise turned out to be higher than acceptable, the active damping system could be kept in a quiescent mode most of the time and activated only to preserve the lock during the bursts of excess seismic activity. The high damping mode can be triggered by external seismometers before the seismic activity burst has had the time to excite the stack's resonant modes and break the lock. During these bursts of activity the interferometer data quality may be compromised by re-injected noise, but just maintaining the locks, even at higher sensing level, would have a greatly beneficial effect of saving the long lock re-acquisition and stabilization times and will improve the sensitivity duty cycle well above the required level.

Practical implementation

Extensive work has already been done to test the viscous damping scheme in real life. A HAM-like prototype has been built with surplus stack springs and instrumented, as shown in picture 1 to 4, using cannibalized instruments from earlier SAS tests. The prototype is presently being interfaced to a d-space DSP module for controls and should provide concept validation in a short time.

The practical implementation inside the LIGO chambers poses several practical challenges.

We need to install the remedial system on the existing in-UHV system without any further machining and in a very short time to avoid intolerable levels of water loads on the chamber walls and stack rubbers. Fortunately suitable anchoring points have been identified on the outer-bottom surface of the cross pipes and on the top surface of the optical bench.

All the components of the system have been already designed to be fully UHV compatible. To speed up the installation time two LVDTs and two actuators (for the vertical and one horizontal degree of freedom) have been cropped up in a shoe-and-boot assembly. Three shoe-and-boots are positioned at roughly 120º around the perimeter of the optical table in almost optimal positions for the 6 d.o.f. viscous damping implementation. The boot carries the actuator permanent magnets and yokes and the large LVDT secondaries. The shoe carries the actuator coils and LVDT primaries. The actual geometry is shown in figures 5 to 8.

The possible positioning of the boots is not far from an ideal configuration for a 6 d.o.f. damping scheme.

Two sets of components are currently being fabricated. One set will be tested in the Synchrotron HAM prototype while the second set is intended to be installed in the LASTI BSC chamber.

An installation procedure has been developed.

Installation procedure:

- Each boot (1) and shoe (3) are positioned one with respect to the other and rigidly connected together by the straps (2) shown in figure 5 and secured by two knobs during transport and installation. The LVDT and actuators are tested and calibrated.
- The boot is mounted hanging from the cross beam structure using existing 1.0” diameter holes with interface plates (figure 8, detail) or the cross bridge ((1) in figure 7) while the shoe, that will eventually be mounted on the top surface of the BSC optical bench, hangs from the boot through the transport strap. The shoe’s support shelf hovers a few mm from the optical table top surface.
- The LVDTs are wired and the readings from all LVDTs are recorded.

- Slots in the shoe’s shelf and in the boot’s interface plate allow for position adjustment with the help of wide washers. The boot’s positioning is tuned to bring the shoe’s support shelf in hovering contact with the optical bench top surface. Similarly horizontal positioning is achieved. At this moment there is still no load applied to the table, so that it is still in its rest position.
- The shoe’s support shelf is fastened to the table's top using straps across the top surface windows. The optical table is now frozen in its original position by the boot-to-shoe straps.
- We now mount accelerometers positioned 60° from the boots.
- We remove from the ballast weight an amount roughly corresponding to the weight of the three shoes their support shelves and the accelerometer.
- We release the knobs and remove the assembly straps. Now the table hovers close to its initial position.
- We monitor the LVDT readout and move and/or remove and add ballast to bring the LVDT readings back to their original value.
- The optical table now is back at its original working point, ready for use.

Cost and Schedule

The production cost bids, made by Mr. Galli, is as follows (the partial totals are added up from the G&M itemized price list):

Boot and shoe, complete with LVDT and actuator, each	Eu	3383
Support structure	Eu	3003

Totals:

3 boots for Caltech’s HAM prototype	Eu	10149
3 boots for LASTI’s BSC prototype	Eu	10149
LASTI cross beam support structure	Eu	3003
Grand total	Eu	23301
Grand total	US$	20150

Excluding coiling costs and electronics and accelerometers.

Linear electronics will cost an estimated 8000 US$ per BSC for the NIM linear drivers of LVDTs, Actuators and Accelerometers, based on TAMA prices)

The SAS horizontal accelerometers, vacuum compatible version, cost 4200 Eu per unit, i.e. 12600 Eu or 10900 US$. For the vertical accelerometers, one would have to rely on an encapsulated commercial item.

Figure 1
Eagle view of the HAM Active Internal Damping prototype.
Visible at 60^{o} intervals are the alternated horizontal and vertical sensing/actuation doublets.

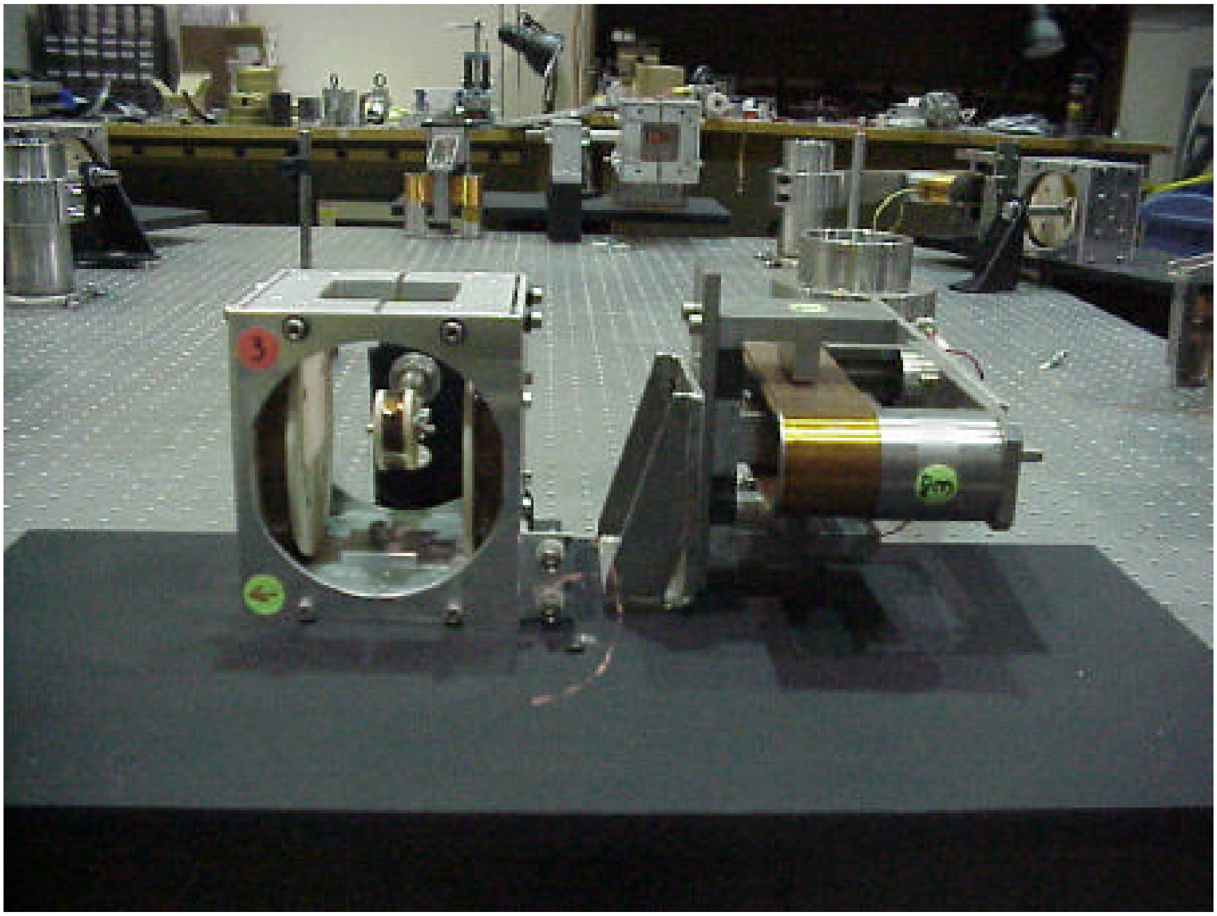

Figure 2:
Detailed view of an LVDT (left) Constant force Actuator horizontal doublet.

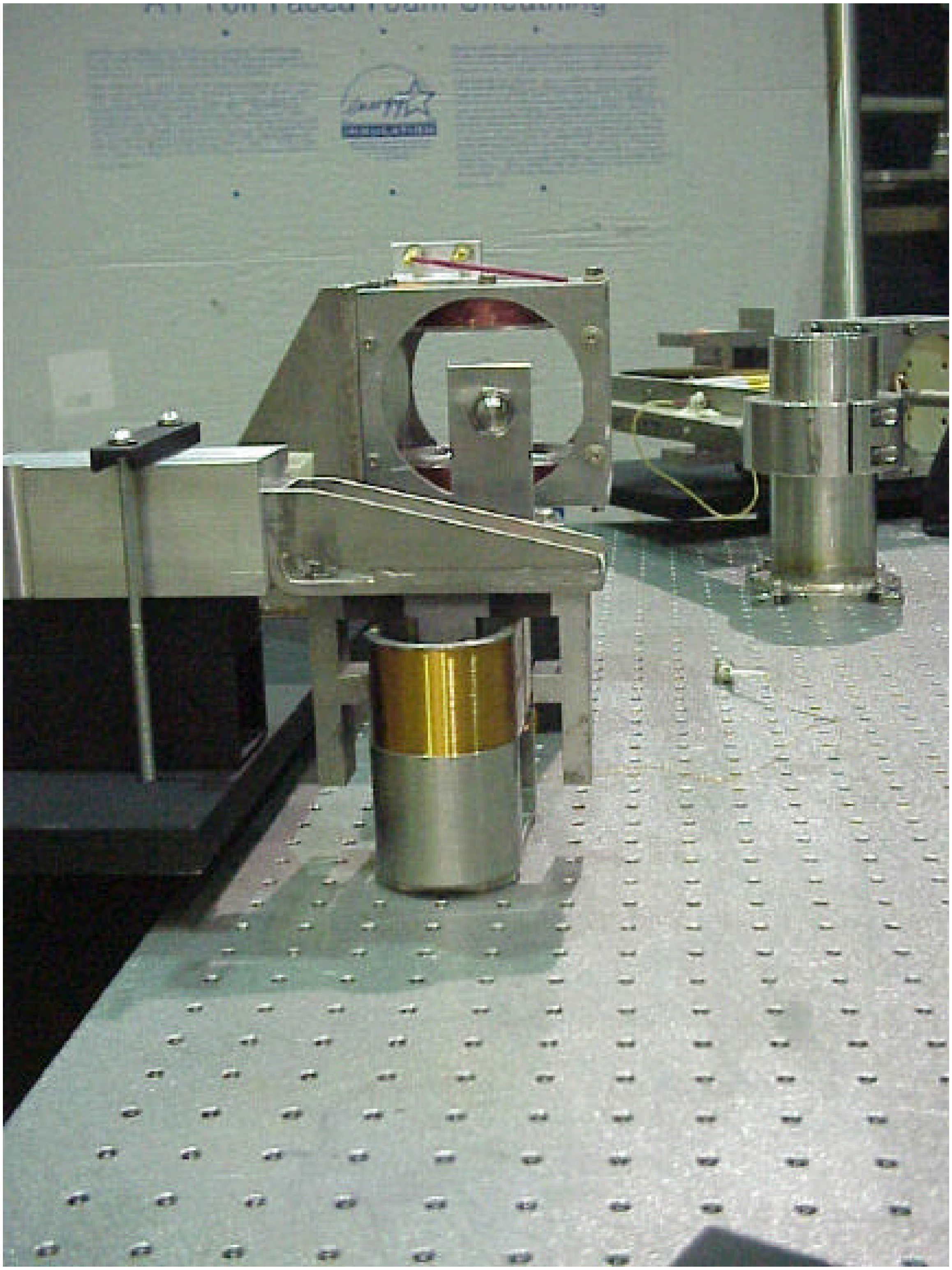

Figure 3:
Detailed view of an LVDT (left) Constant force Actuator vertical doublet.

Figure 4

Side view of the HAM Active Internal Damping prototype and detail of a stack.

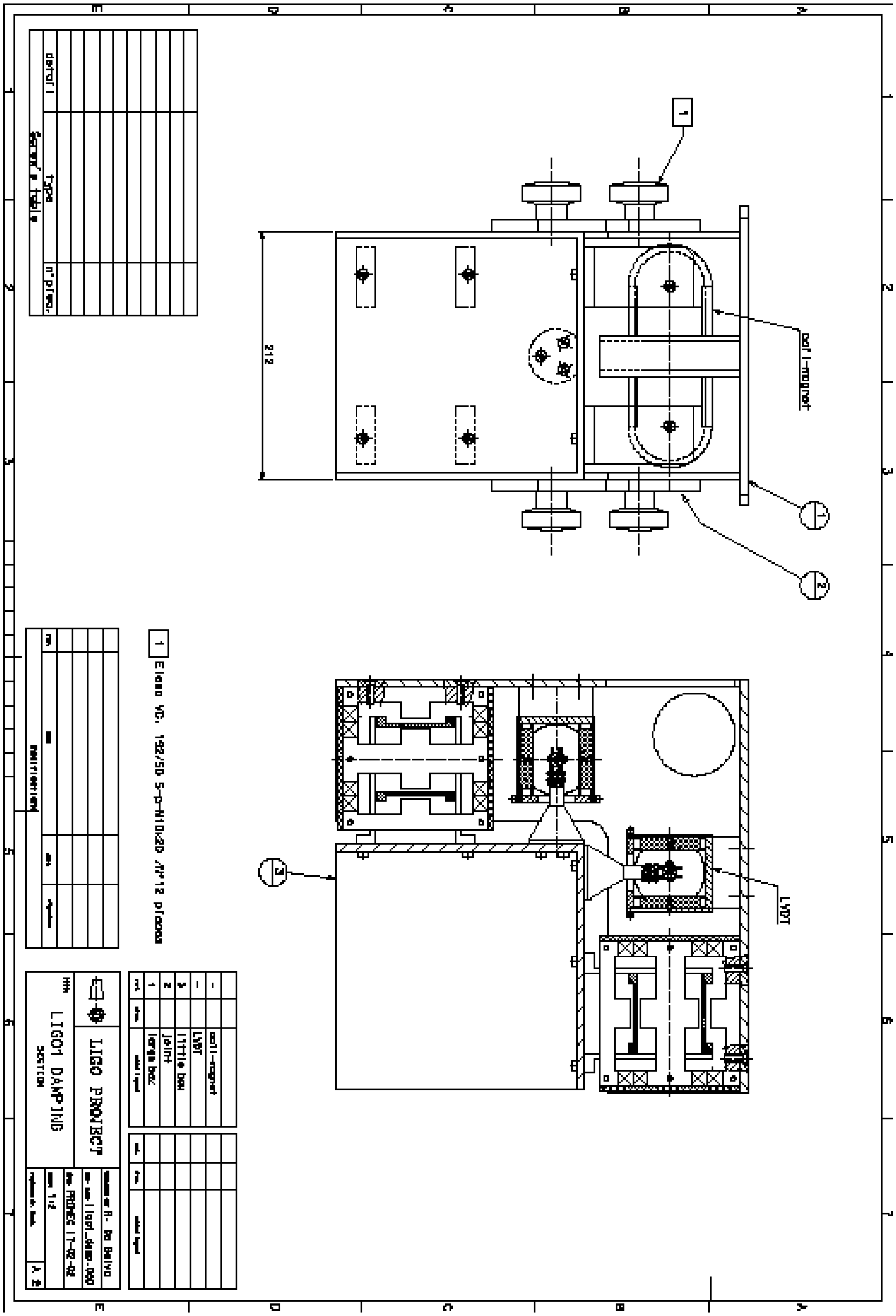

Figure 5: Positioning of LVDTs and Constant force actuators inside the boot-and-shoe arrangement. Two straps locked by transport knobs tie the she into the boot during transport and installation.

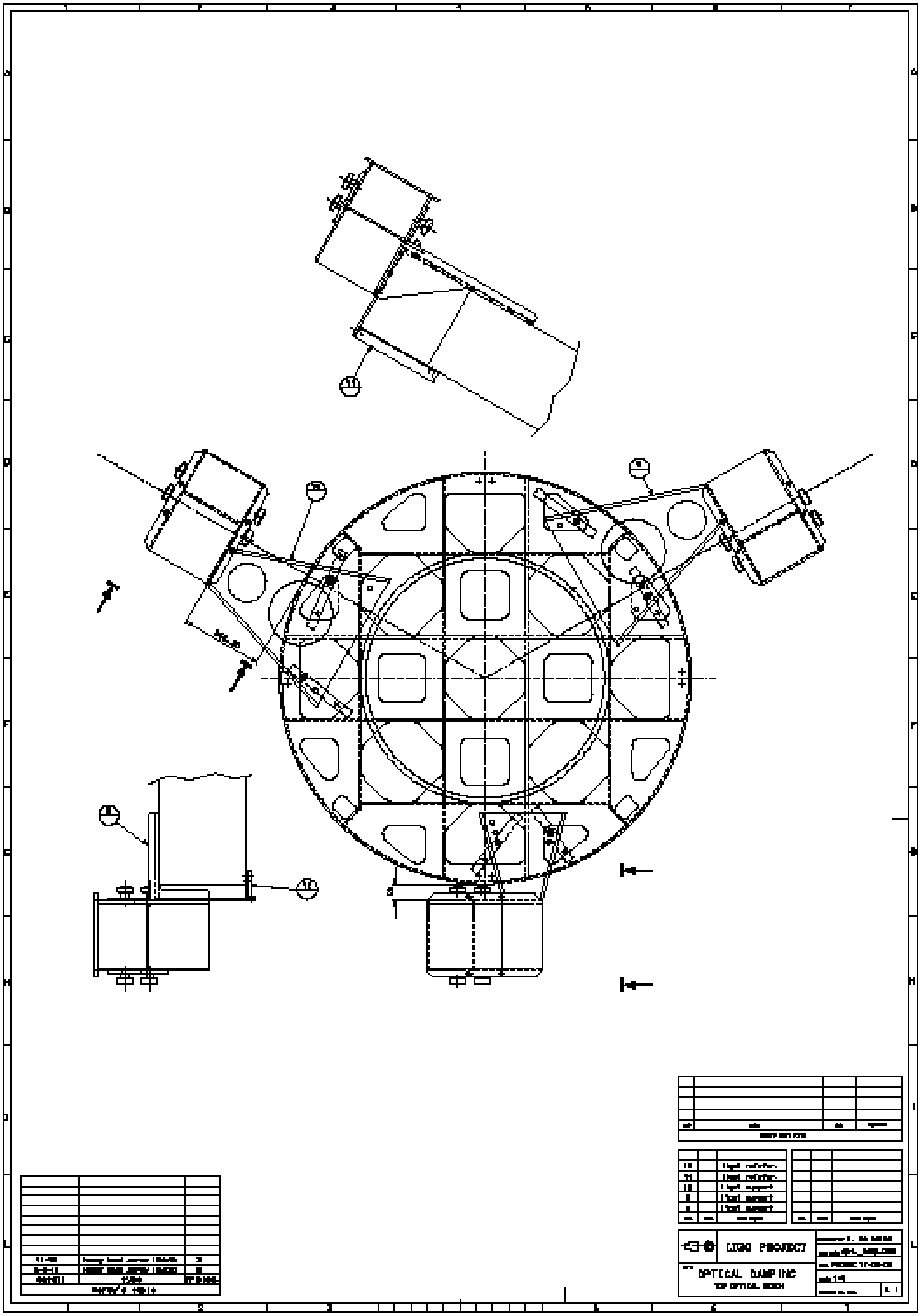

Figure 6: Positioning of the three boots around the BSG optical table. The close to 120° distribution is almost ideal for optimized viscous damping algorithms.\

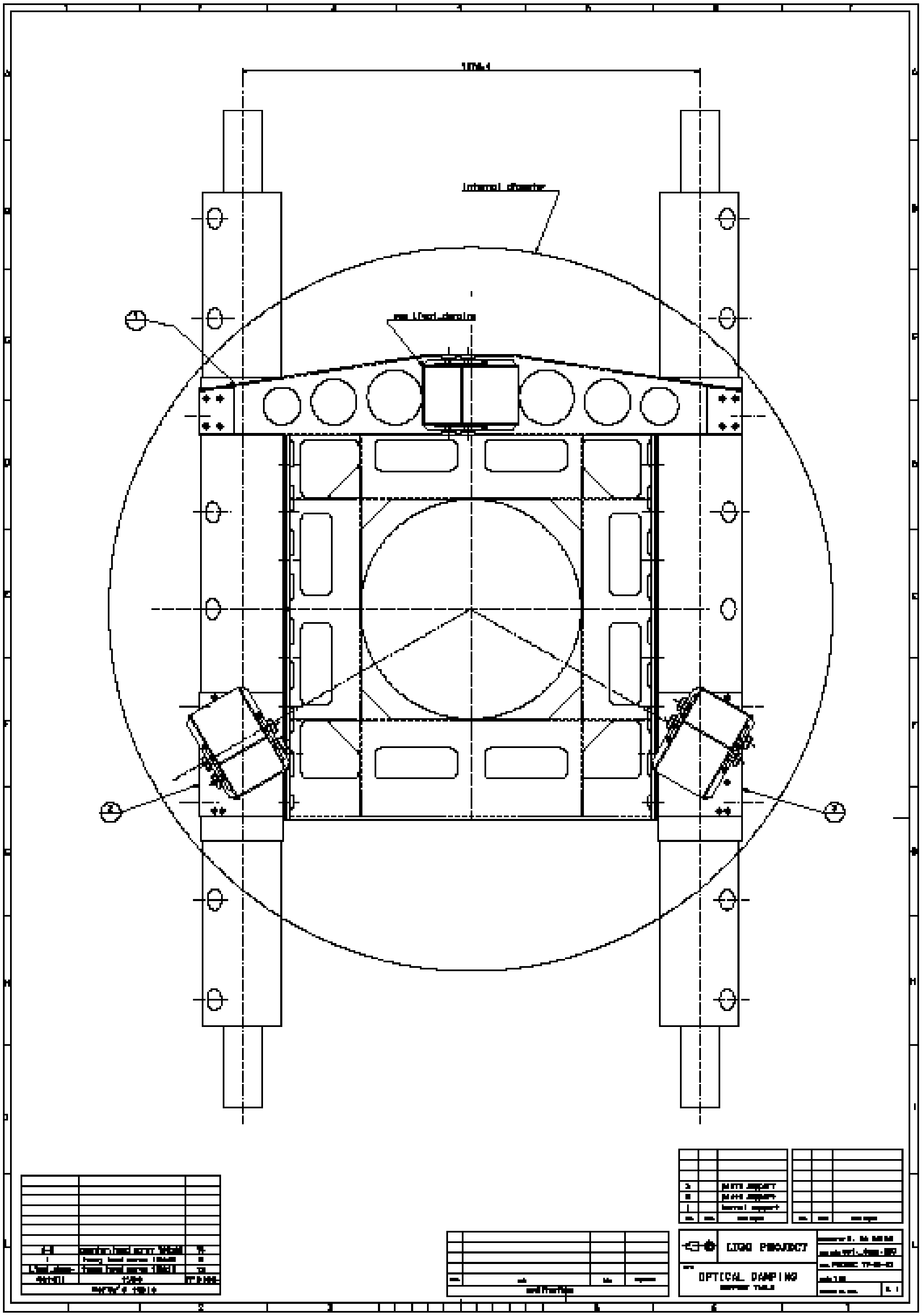

Figure 7: Support structure used to tie the three boots to the cross beams, the two lateral ones hang directly from the two cross pipes while the central one is supported by a U-channel.

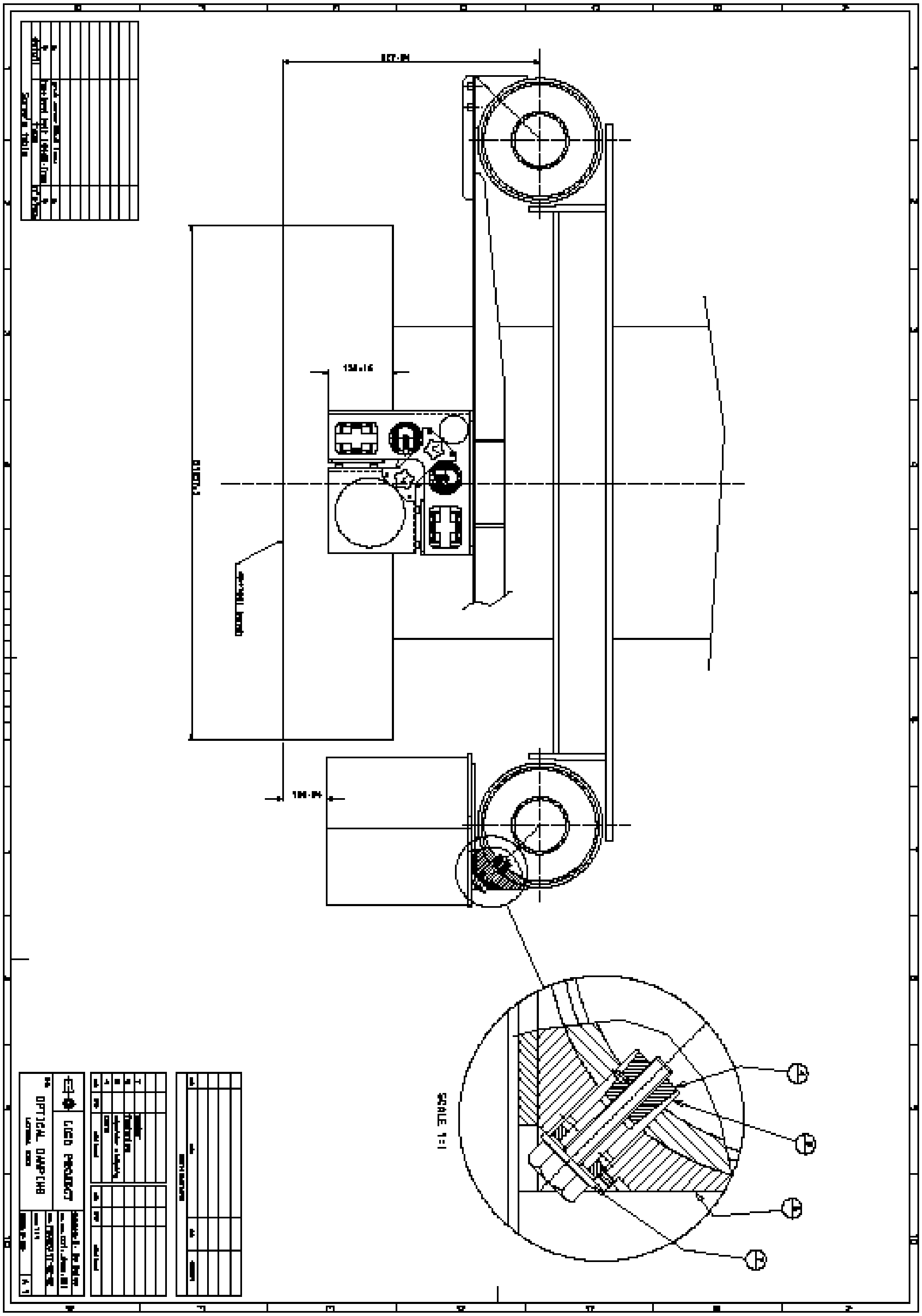

Figure 8: Detail of the attachment of the boots from the cross beams.

References

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1 Rai Weiss reports G-010325-00M and 1011236204

2 LIGO-T-020033-00-D

3 http://www.ligo.caltech.edu/docs/P/P010035-00.pdf

4 http://www.ligo.caltech.edu/docs/P/P010026-02.pdf

5 Sannibale, V., Thèse de Doctorat France 26-Jun- 98 “Le système d'alignement du banc de détection de l'expérience VIRGO de recherche d'ondes gravitationnelles. “ Université de Savoie

6 LIGO- T020038-00-R “Applying the SAS Know-How to produce remedial solutions to the LIGO seismic isolation shortfall; 2: Passive External Isolation and Stack Damping”