LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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OMC Suspension Final Design Document

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Contents

Section 1: Introduction
Section 2: Requirements and Specifications
Section 3: Mechanical design
Section 4: Suspension thermal noise, transfer functions and seismic noise estimates
Section 5: Results from the Enhanced LIGO prototypes and related work
Section 6: Electronics design
Section 7: Re-use of Existing Suspension Parts
Section 8: Final design review design checklist
Section 9: Conclusions

1 Introduction

The purpose of this document is to describe the final design of the output modecleaner suspension system (OMC SUS) and present evidence that the design satisfies the requirements/specifications. The conceptual design was presented in T060257-03. Details of the design were presented at an LSC meeting in March 2007 (G070062). The design was reviewed in November 2006 and December of 2006 (construction review) prior to construction and testing of the first OMC SUS which took place during 2007 at Caltech. This prototype was sent to LLO during January 2008 for installation in Enhanced LIGO. In August/September 2007 a further review was held (Prototype #2 fab readiness review). This was not a full preliminary design review. Its purpose was to allow us to proceed to build the second prototype for Enhanced LIGO for LHO, in particular to allow us to expedite long lead items, namely the support structure and the blades. The report from this review is M070359-00. Further information on these reviews can be found on the OMC SUS wiki at

http://ilog.ligo-wa.caltech.edu:7285/advligo/OMC_Suspension#reviews

It was agreed that the experience gained in installing and using the OMC SUS at the two observatories for Enhanced LIGO would serve as a test of the preliminary design and hence we are progressing to a final design review without having formally completed a preliminary design review.

v2 – revision of document, February 2014. After the final design review was completed, with report L0900064-v5 being produced, the design of the suspension has undergone some changes, primarily as a result of changes to the “payload” – the OMC bench. Thus we are updating this document to capture these changes. In summary the most significant change is to the method of attachment of the suspension wires to the OMC bench, discussed in section 3.2, and this change has affected the dynamics of the suspension, in particular the pitch modes. Another change is to the earthquake stop design around the bench, discussed in section 3.3. These two changes and their consequences are covered in this revision to the original document. Another point to note – the name OMC SUS, has been shortened to OMCS in recent references.

2 Requirements and specifications

The requirements/specifications for the OMC suspension are given in T070189. Included in this document are comments added at the time of the 2nd prototype readiness review in Aug/Sept 2007, and further updates since that time. These specifications give general requirements on the payload to be suspended and method of suspension. Numerical noise requirements had not been set for the OMC SUS before the review. However the report L0900064-v5 under Finding 1) states: “the required motion of the OMC is $x_{omc} \leq 10^{-13}$ m/√Hz above 10 Hz.”

In section 4 we give the expected thermal noise and seismic noise performance compared to this requirement.

3 Mechanical Design

The basic mechanical design is that of a double pendulum, with the OMC bench forming the lower mass. There are two stages of vertical isolation provided by two sets of blades, one set of two at the top of the suspension and a second set of four within the top mass. See figure 1. With such a design, all twelve rigid body modes lie below 10 Hz. It was noted that using an upper mass of 3 kg,

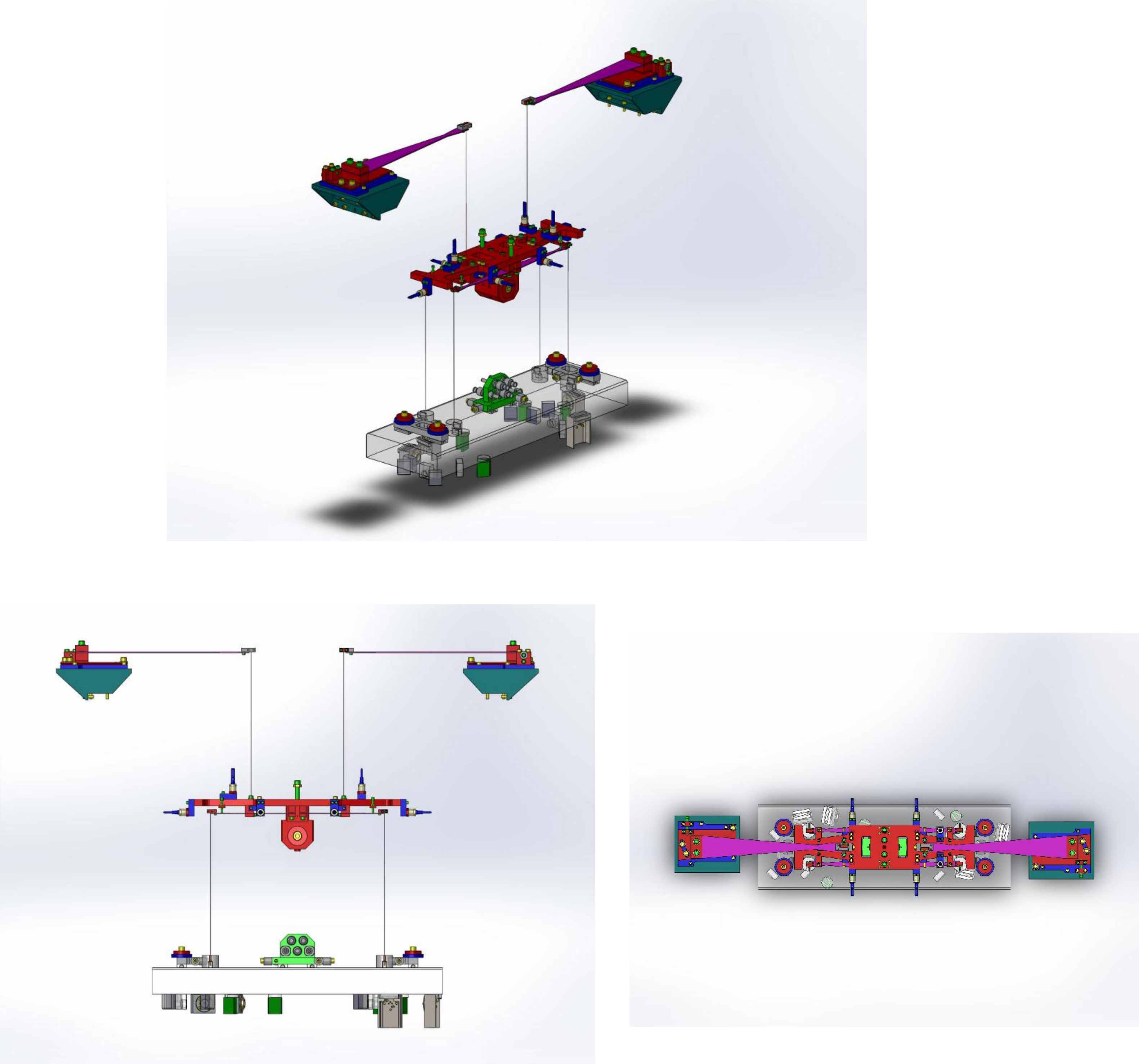

Figure 1: Three views of the OMC suspension (with the support structure removed).

Top: iso view, bottom left: side view, bottom right: top view together with the proposed OMC bench mass of 6 kg would give a total suspended mass of 9 kg – the same as in the IMC triple (now HSTS) design, whose three stages are each 3 kg. Thus several elements of the input modecleaner design including the blades, the top mass and the general layout of the OSEMs used for damping were adapted for the output modecleaner, saving on design effort. Indeed the first prototype OMC suspension delivered to LLO used spare IMC blades. However the mass of the OMC bench in fact ended up at 6.9 kg which means that the blades in the LLO prototype are more highly stressed than they were designed for. Thus for the second prototype, which was delivered to LHO, slightly thicker blades were procured to take the extra mass. For this reason, and due to several other small design modifications made after the first prototype, the LHO design serves as the basis of the final design presented here.

The assembly of the suspension is carried out in the first instance with a dummy metal bench, whose mass, moments of inertia and method of suspension all mimic the optical bench. Thus we can carry out assembly and initial tests of alignment and damping without using the optical bench.

3.1 Support Structure

The support structure for the suspension consists of a welded aluminium box shape with bolted sections at each corner. See T070205-04-D (T070205-v3) and references therein for more details. See figure 2 which shows a rendering of the whole assembly and a picture of the assembly in the tank at LLO.

It can be seen in the picture in fig. 2 that there is wiring from the OMC bench. This wiring goes directly to the structure. Originally the intention was to attach the wiring to the top mass and then to the structure to reduce any adverse effects on isolation. However it soon became apparent in bench tests that the wiring was heavy enough to cause problems in alignment and so it was rerouted directly to the structure. This could cause degradation in isolation. An initial study (T070304) suggested that the isolation would not be significantly affected. However this analysis used a simplified model. More recent work by SURF students has arrived at the same conclusion (discussed further in section 5).

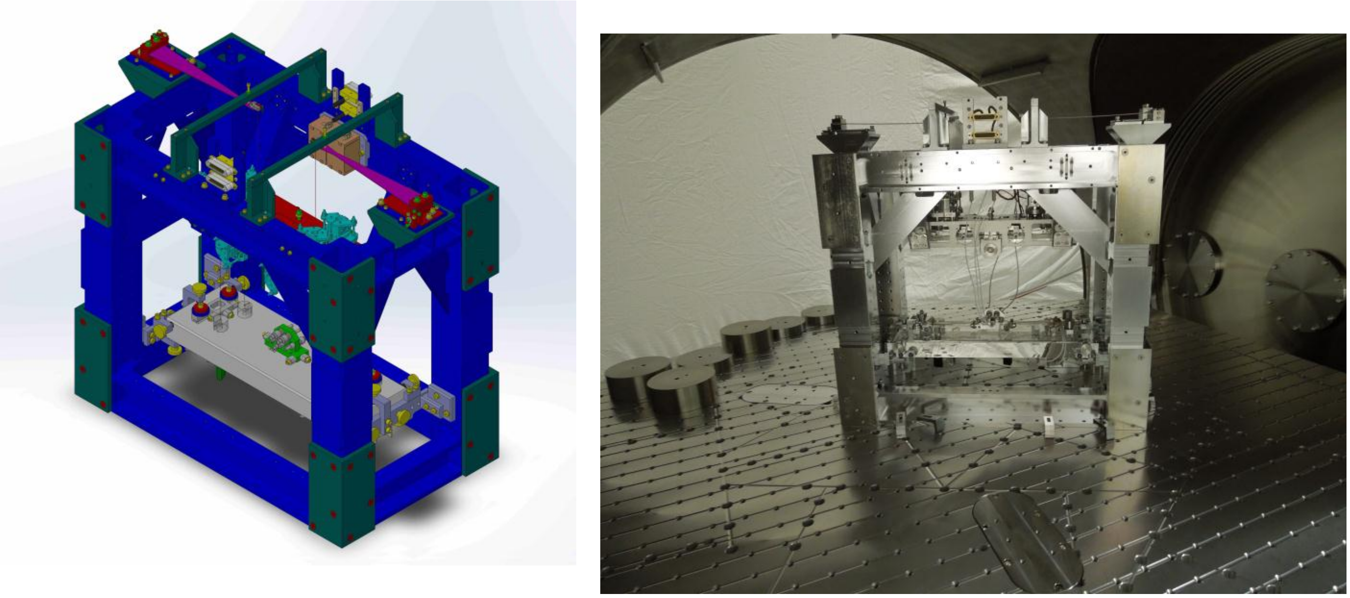

Figure 2. OMCS full assembly. Left: Solidworks rendering, right: OMCS installed at LHO (in HAM6).

3.2 Method of Suspension of OMC Bench

The method of suspension of the bench used in eLIGO and presented at the aLIGO final design review in 2009 was as shown in the lower set of images in slide 7 of G070062, and involved using through holes in the glass bench. However this has since been superceded with a new design which does not involve the need to cut holes through the bench, and thus makes the process of manufacturing and hanging the bench simpler.

The new method of attachment of the suspension wires to the bench involves the use of fused silica wire brackets (D1102209) designed to be UV bonded to the aLIGO fused silica bench. These new brackets were not compatible with the original lower wire clamps. A new design of clamp, D1200971, using beryllium copper was designed to be crimped onto the 0.0079" (0.20 mm) diameter suspension music wire and still fit into the available space in the fused silica wire brackets. The clamps provide two cylindrical sections to be crimped; both above and below the cone shaped feature which engages with the wire brackets. Figure 3 shows a close up of the clamp being crimped around the wire and the clamp within the wire bracket attached to the top of the bench. Further details on the development of the lower wire clamp and the crimping and testing procedure can be found in T1300081.

One significant consequence of this new design is that the physical break-off point for the wire attaching to the bench is now several centimeters above the centre of mass of the bench, having previously been ~2 mm above the centre of mass. This in particular raises the lower pitch mode frequency from ~ 0.8 Hz to ~ 1.9 Hz. The full set of suspension mode frequencies are given in section 4.3.

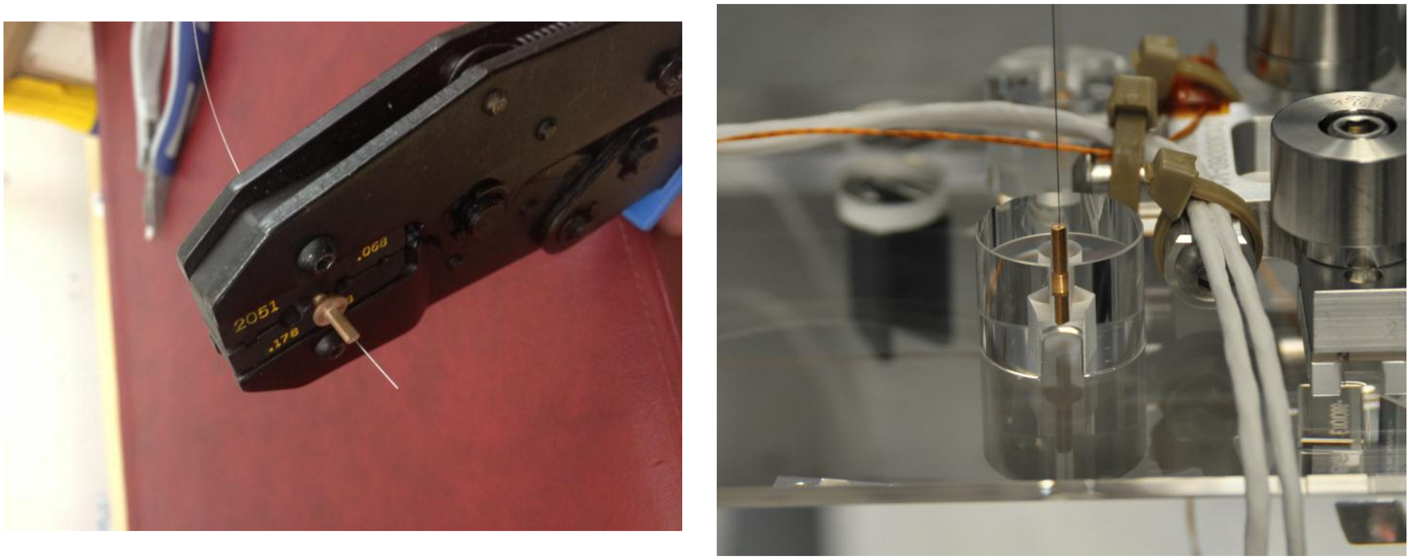

Figure 3. Left: Lower wire clamp being crimped around wire. Right: lower wire clamp within the silica bracket glued to the bench

3.3 Earthquake Stops

The eLIGO OMC had some problems with the earthquake stops touching, slipping, and being awkward. The revised aLIGO design goes to some effort to manage all the earthquake stop functions from the short edge and corners of the OMC. As shown in figure 3, the EQ stops are located only at the edge, clear of the laser paths. The EQ stops are actuated by hand using the large knurled knobs. Like the ISI, the EQ stops are located knowing the dimensions and expected position of the OMC. The EQ stop screws have a side mount retaining ring that sets the maximum EQ retraction (should be about 1 mm) and doubles as a jam nut. The correctly extracted position jams the screw against the retaining ring. As designed here, the vertical and transverse EQ stops have adjustable slots to match the OMC position. The longitudinal stop is not adjustable and so it has a larger extraction range. The stops have peek tips. Drawing number of the Earthquake Stop Assembly is D1201441.

3.4 Overall Assembly

The OMCS overall assembly is shown in D0900295.

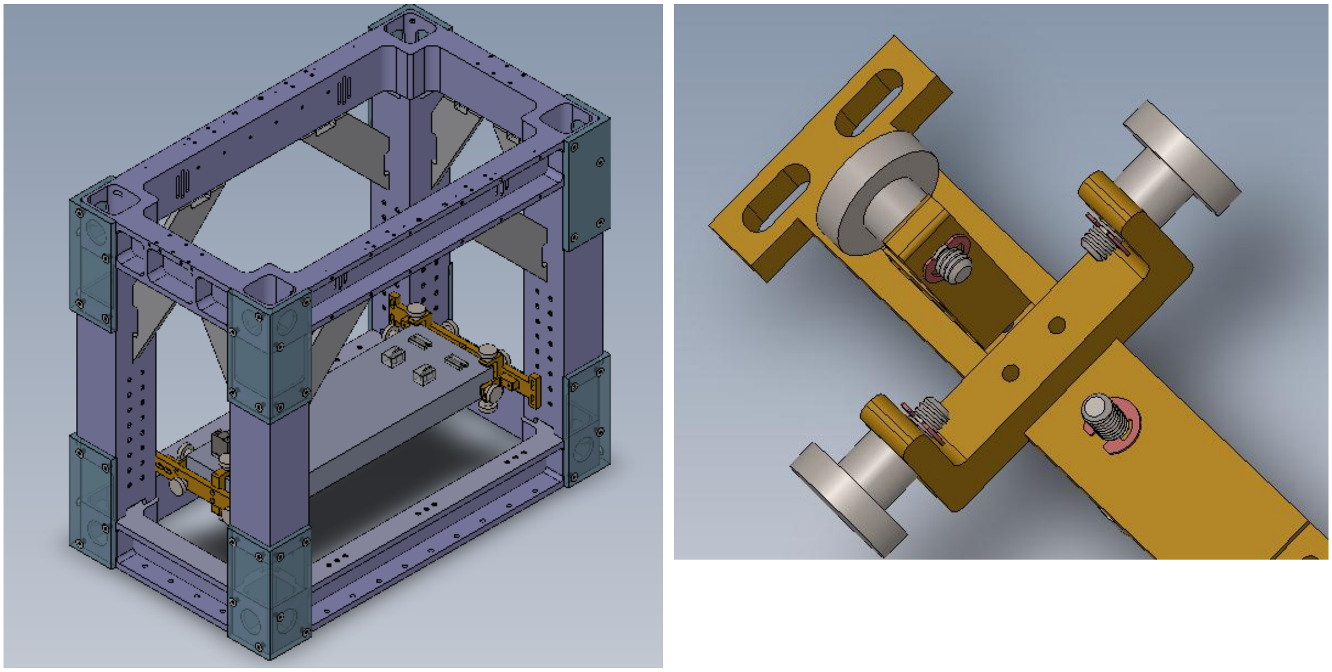

Figure 3. Revised design of earthquake stops. Left: stops shown in situ, right: close-up of stop.

4 Suspension thermal noise and seismic noise estimates, and mode frequencies.

4.1 Thermal noise estimate

A thermal noise estimate has been produced by Mark Barton using a Mathematica model of the suspension which includes Brownian and thermoelastic contributions. See this wiki for more information on the Mathematica suspension models, with a link to the SUS SVN depository where models are kept under version control:

https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/MathematicaModels

The value of the intrinsic loss (ϕ) in the wire assumed for these curves is 2x10^{-4} (ref G Cagnoli et al Phys Lett A 255, p 230, 1999). The wire radius of the lowest stage of the suspension is 1.01 x 10^{-4} m. Figure 4 shows the thermal noise contributions from various directions (longitudinal (= x), pitch, yaw and vertical) and the quadrature sum, compared to the requirement. In the OMC suspension, the beam enters in the x direction, initially striking a mirror offset 192 mm in y and -36 mm in z (up) from the COM. See figure 5. These large offsets lead to significant (dominant) contributions from yaw and pitch as can be seen in figure 4. In particular below 0.5 Hz the yaw contribution dominates, and by 1 Hz and above the pitch dominates. The assumption of a cross-coupling level for vertical to x of 0.001 is optimistic in this suspension due to the presence of the electronic cabling from the OMC bench directly to the structure. See section 5 below, where the eLIGO results suggested a value of ~ 0.03 in that case. However, even if we took a very conservative value of 0.1 for this cross-coupling, the vertical contribution would still lie significantly below noise coupled from pitch. It should also be noted that the intrinsic phi value used for loss may be optimistic due to the revised design of crimped clamp described in 3.2 above, which may introduce some frictional loss, increasing phi. (Note that phi enters as square root into displacement noise, so an increase of, say, a factor of 10 leads to a factor of 3 increase in noise). However it is clear that there is a large margin between the estimated thermal noise and the noise requirement, around 250 at 10 Hz and increasing with frequency.

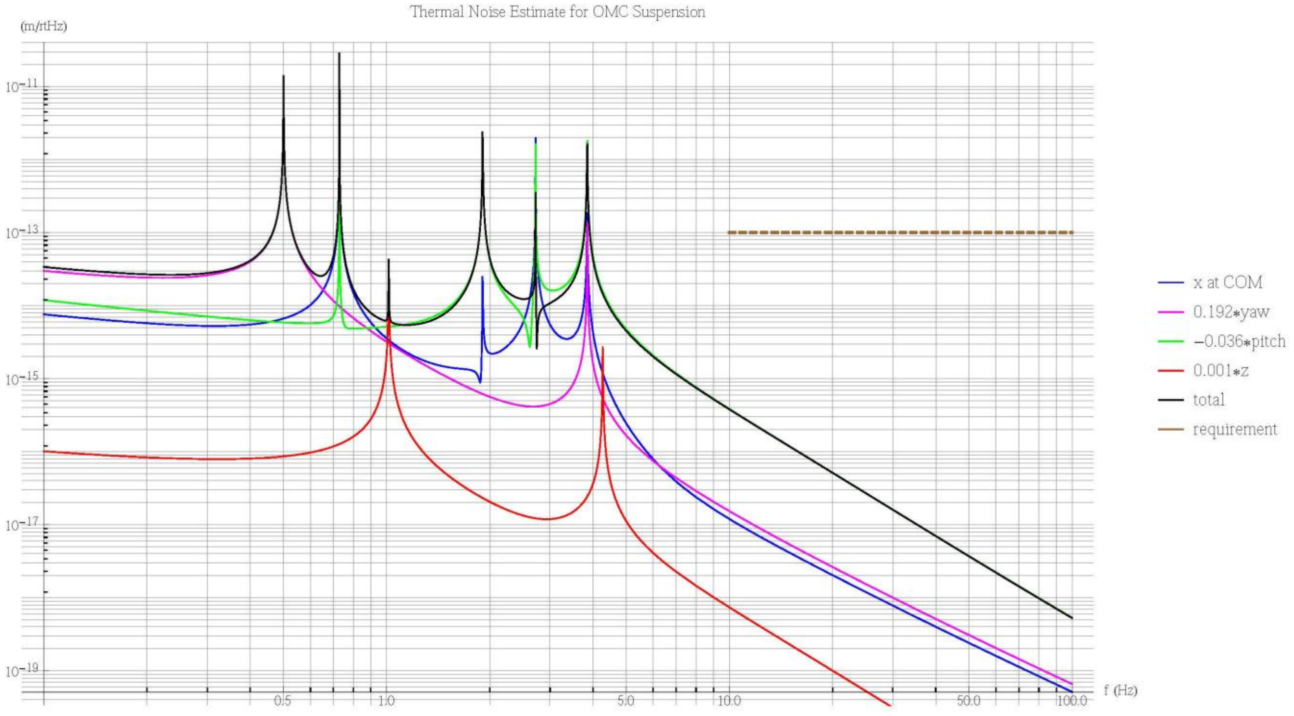

Figure 4. Thermal noise estimate for OMC suspension: Various contributions and their total are shown, as identified in the legend. The overall noise requirement is also shown.

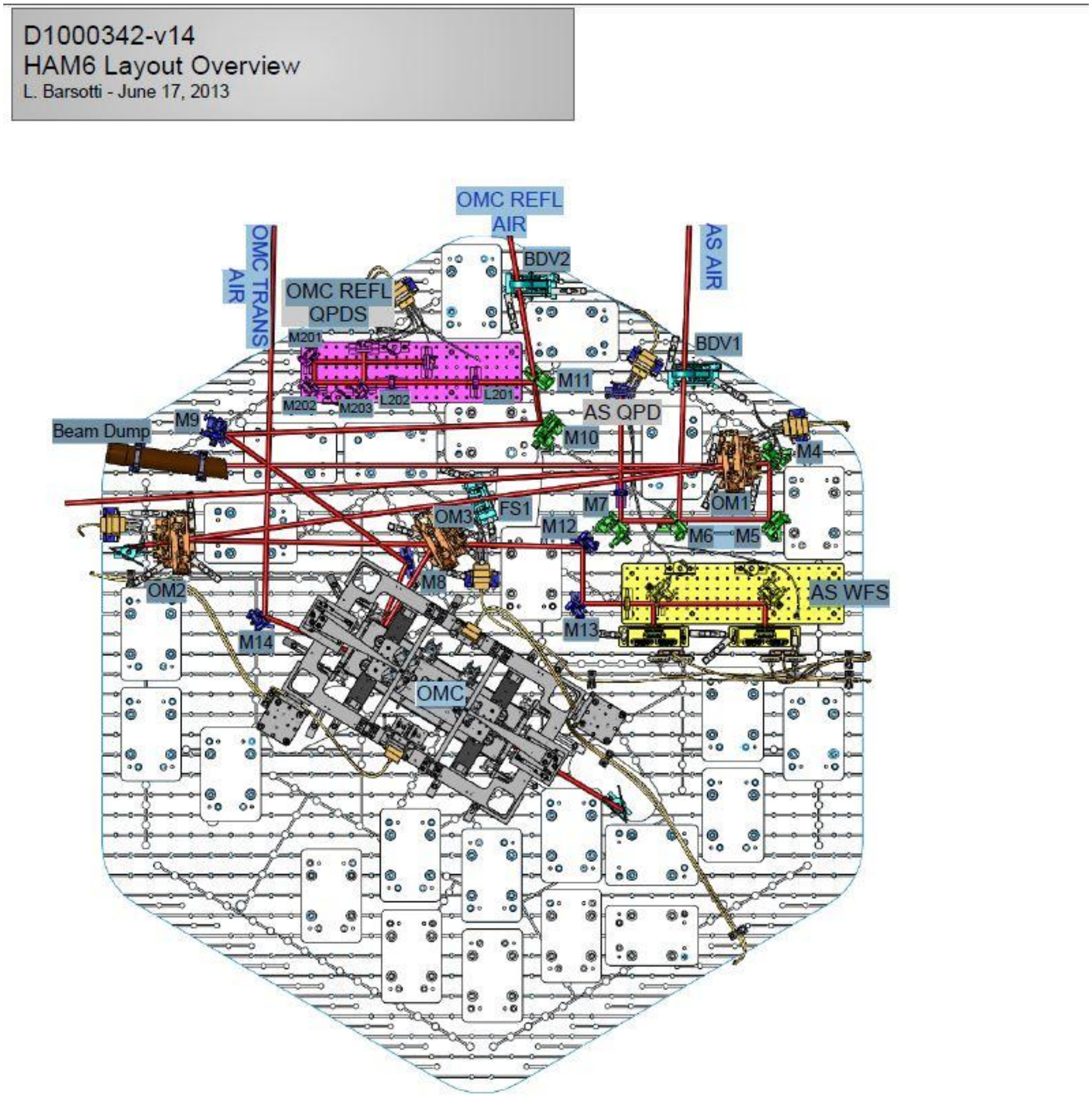

Figure 5. Layout of HAM6 chamber showing placement of OMC and laser beams (in red). (Placeholder diagram). The input beam strikes the OMC towards top left in this view

4.2 Seismic Noise Estimates

Figure 6 shows various seismic noise estimates for the OMCS attached to a HAM-ISI, compared to a requirement curve of 10^{-13} m/√Hz at 10 Hz and above. The OMCS model and parameters are taken from the SUS SVN which is found at

https://redoubt.ligo-wa.caltech.edu/websvn/listing.php?repname=sus&

The parameter file is omcsopt_metal rev 4904. Active damping has been added to achieve ~10 sec decay time using the GEO active filter design as an example (see T0900435 section 11.5 for more details of that filter design.). With other filter designs the curves will vary slightly. The HAM-ISI noise levels assumed are using the baseline HAM-ISI spec (1/f below 0.2 Hz, 0.2 Hz=2e-7, 0.6 Hz = 6.67e-10, 1 Hz = 4e-10, 1/f from 0.6 to 30 Hz, flat above 30 Hz at 1.33e-11), where the numbers are m/√Hz for translations and rad/√Hz for angular motions. Coupling of 0.001 for vertical and lever arms of 192 mm in yaw and 36 mm in pitch have been used. A longitudinal sensor noise curve is also shown, where the sensor noise has been included in the same way as described in T0810039.

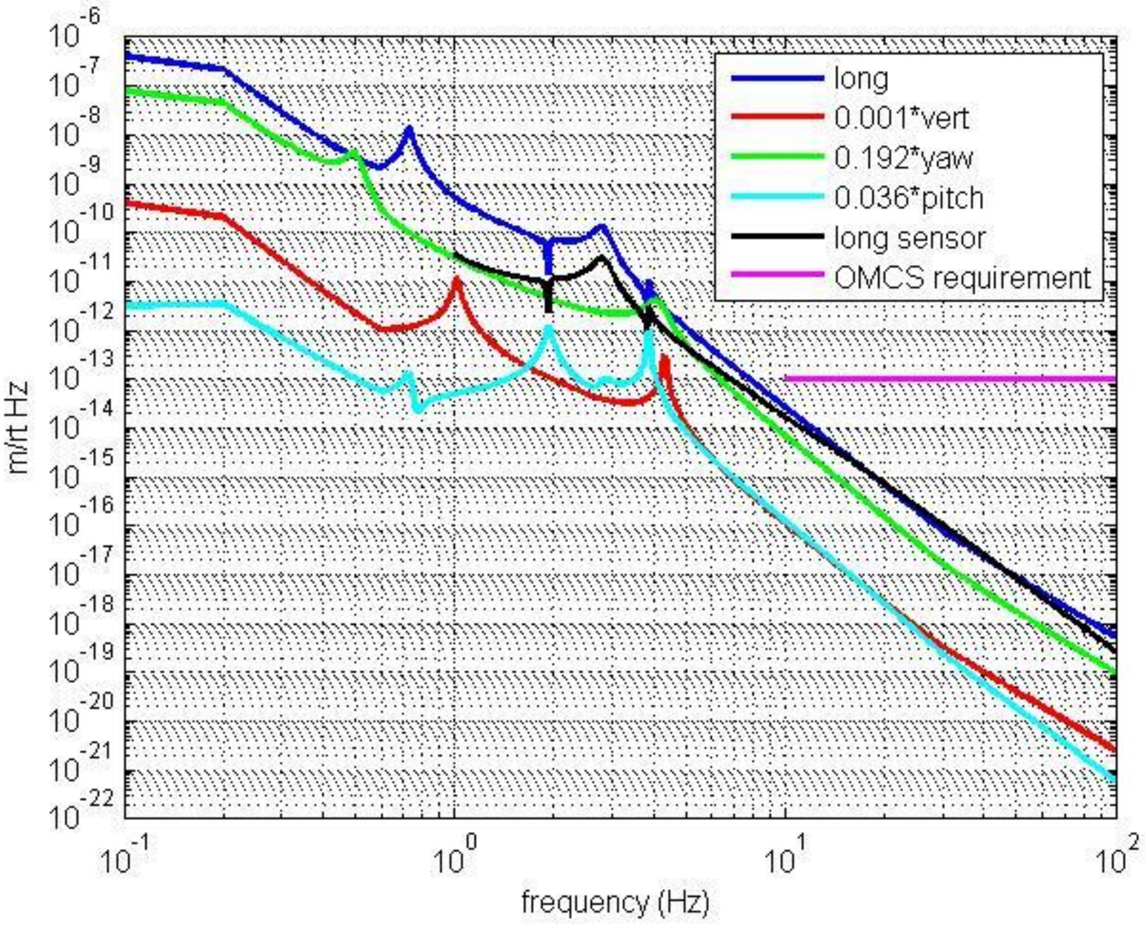

Figure 6. Various seismic noise and sensor noise estimates, as described in the text.

It can be seen that all the predicted curves lie below the requirements level. As discussed in 4.1, the vertical coupling is likely to exceed 0.001, but even with substantially larger coupling the vertical noise would lie below the requirement. A more precise analysis of the predicted angular cross-coupled levels of noise would require taking into account the detailed positioning of the OMC structures on the HAM-ISI tables. However the estimates shown here should be in the right ballpark and clearly show that the predicted noise contributions lie significantly below the requirements.

4.3 Mode frequencies.

The rigid body mode frequencies of the suspension are all below 10 Hz and fall into a range from ~0.5 Hz to ~ 7 Hz. In detail they are as follows (in Hz):

Longitudinal and pitch: *0.728*, 1.907, *2.722*, 3.849

Yaw: 0.500, 3.852

Transverse and roll: *0.722*, 0.963, *2.625*, 6.762

Vertical: 1.015, 4.274

Italics indicate the modes which are more associated with longitudinal or transverse motion.

5 Results from the Enhanced LIGO prototypes and related work

Several tests on the OMC suspension have been carried out at the two sites. Transfer functions have been taken which show that the predicted mode frequencies and general behaviour agrees well with the MATLAB model. See figure 7 which shows data taken at LLO (see D Bridges entry on LLO elog 15th Jan 2009 for further details) compared with the expected transfer functions using the MATLAB model. The transfer functions are taken open loop from force or torque input to a particular direction (using the appropriate matrix of OSEMs) to the resulting motion in that direction. Note that no attempt was taken to match the Q's. See late in this section for comments on Q's. Also the y axis magnitudes are not directly comparable.

Damping has also been investigated on the LLO OMC suspension. This has been written up in T0900071-v1, which includes details of how the plots were made and what damping function was used. These results were taken by putting in a step input on and then off from the HAM-ISI and observing the responses. This was carried out for the six degrees of freedom. It can be seen in that document that the local damping can easily provide decay times less than 10 seconds in all degrees of freedom. We show in figures 8 examples for the longitudinal and vertical directions.

We also observe that there is significant natural damping occurring. We can make a rough estimate of the magnitude. For the longitudinal direction the 1/e decay is ~ 40 seconds, and with a dominant frequency (the lower long. frequency) of 0.7 Hz this corresponds to a Q for that mode of ~ 90. A similar calculation for the vertical direction gives a Q of ~ 70. We attribute this damping to the (necessary) electronic cabling which goes from the OMC optical bench to the structure.

Another observation from the data in T0900071-v1 can be made by comparing the induced motion in the longitudinal when excited in the longitudinal direction and when excited in the vertical direction with the same magnitude of input motion on the HAM-ISI table. The ratio (x out from x in) / (x out from z in) appears to be approximately 30, implying a cross-coupling factor of 1/30 or ~0.033. Again we attribute this cross-coupling to the presence of the electronic cabling.

The effects of such cabling have been investigated as a SURF student project in summer 2008. The results obtained from that work suggest that we are observing at LLO more damping and cross-coupling than expected from modeling. See student reports T080341-00-R and T0900083-v1. We are currently looking more closely into this and a further report building on the student work is in preparation. It appears from pictures of the two OMC SUS systems in situ at the observatories that the cabling arrangements may not be the same – with some twisting or at least touching of the two cable bundles in the case of the LLO OMC, whereas at LHO the arrangement more closely represents what was modeled and intended, with two separate cable bundles. We are checking on whether there are other differences. At present we do not have damping measurements at LHO but are investigating having this carried out. Clearly we want to minimise the affect of the cabling by dressing it as cleanly as possible without excess rubbing and so we would advise the ISC group to take care over this when the Advanced LIGO OMCs are installed. Whether the level of damping currently seen at LLO is considered too high is still to be ascertained. More information may be forthcoming as ELIGO proceeds.

The first structural resonance of the OMC suspension has been observed on the Hanford OMC in studies of the HAM-ISI behaviour, as reported in T080274-00-D (see section 4.3). It was deduced that the first resonance was seen at ~ 103 Hz in one position and when the OMC was moved to another position it was seen at 110 Hz (presumably the rigidity of attachment was changed

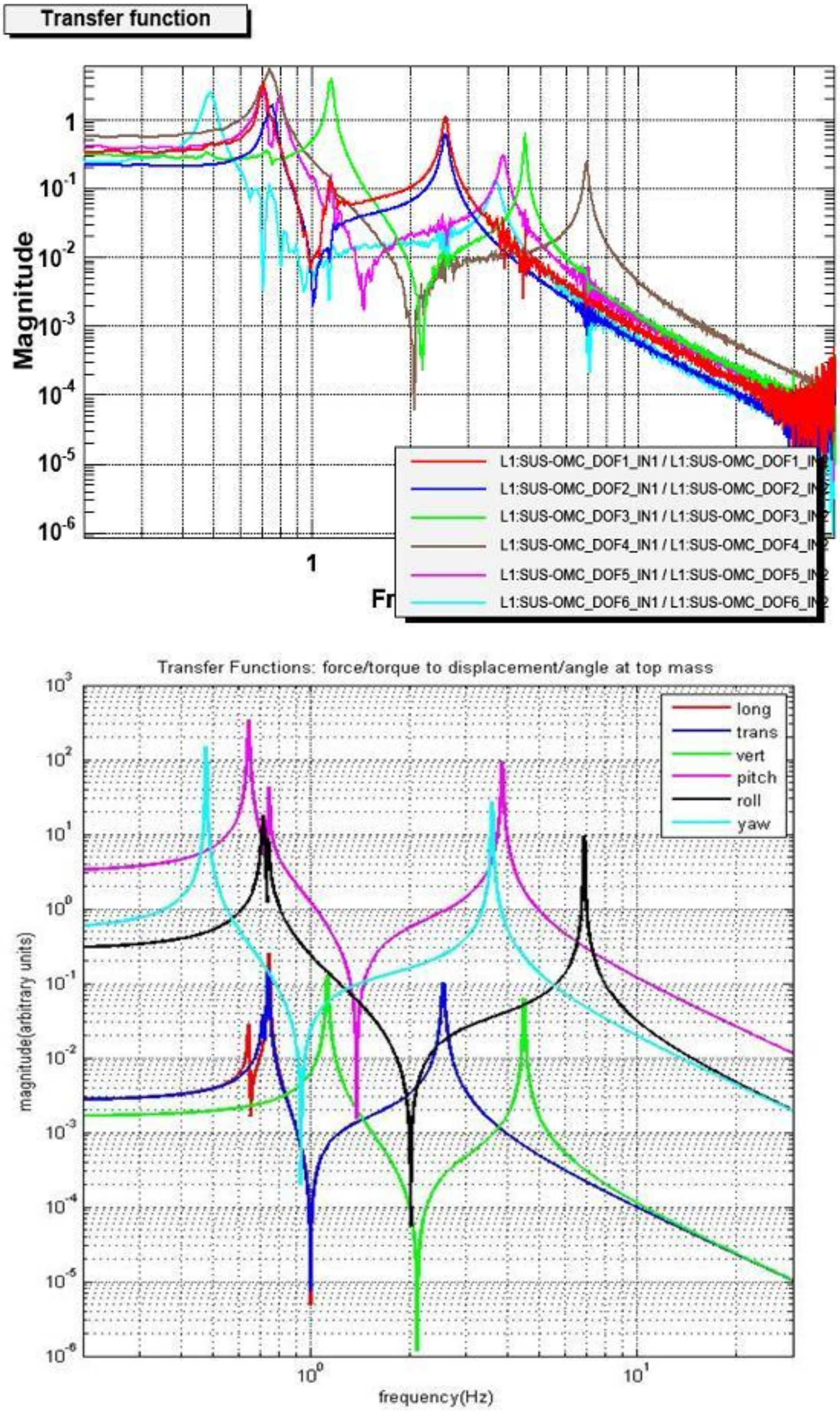

Figure 7. Comparison of experimental (above) and modeled (below) transfer functions for the LLO OMC SUS as described in the text. Note that colours correspond, except brown above = black below.

slightly). Those measurements can be compared to a measured value on a stiff table when well attached of ~140 Hz, ref T070205-04-D. We would have expected a value closer to ~ 140 Hz in situ. We understand however that the structure was attached by only 6 screws to the HAM table. We advocate using more screws, or preferably dog clamps, to attach the structure, as described in the Lessons Learned document, E0900049-v1.

6 Electronics design

The electronics for the Advanced LIGO versions of the OMC SUS are formally a joint UK/US responsibility, as for other suspensions. However the electronics for the Enhanced LIGO versions of the OMC SUS were wholly a US responsibility, apart from the Birmingham OSEMs (BOSEMs) which were supplied as part of the UK prototype deliveries. Thus designs for all the electronics already exist and have been implemented. Links to schematics are posted on the review wiki along with electronics requirements documentation and a block diagram of the Enhanced LIGO OMC SUS and ISI controls.

Regarding watchdog software, that software is in place at the observatories, and can be implemented as required. Both hardware and software watchdogs are provided as part of the standard front end control system. The conceptual design for the LIGO watchdog system is presented in LIGO document number T080127, “AdL CDS Standard Watchdog System Conceptual Design”.

7 Re-use of Existing Suspension Parts

Note added February 2014: points 1) to 4) below are essentially now redundant. The decision was taken not to re-use the eLIGO OMCs. The aLIGO OMCs and their suspensions are built from new parts, including blades redesigned for the new load and nickel plated.

We seek advice from the FDR committee as to which parts of the existing installed OMC suspensions can be reused in Advanced LIGO. We note several issues.

1) The LLO suspension incorporates stainless steel 303 in several of the machined parts. That type of steel has now been removed form the LIGO vacuum compatible materials list except for fasteners. See VRB note L080044-v1.

2) The LLO suspension uses spare IMC blades which are not designed to take the stress level currently being used. The top blades were designed to take 9/2 kg and are currently loaded with 9.9/2 kg (10% over the design value). The lower blades were designed to take 6/4kg. They are currently loaded to 6.9/4 kg. (15% over the design value). Whereas the actual stress level is acceptable at around 800 MPa for the upper blades and less for the lower (noting we use stress levels in quad blades up to 1 GPa), the blades were shaped to take lower mass and hence they are noticeably curved rather than flat in use, with angled clamps used to launch them at an upward angle to compensate for the droop. This may lead to some non-linear behaviour, although we have not seen anything particular in tests of the suspension.

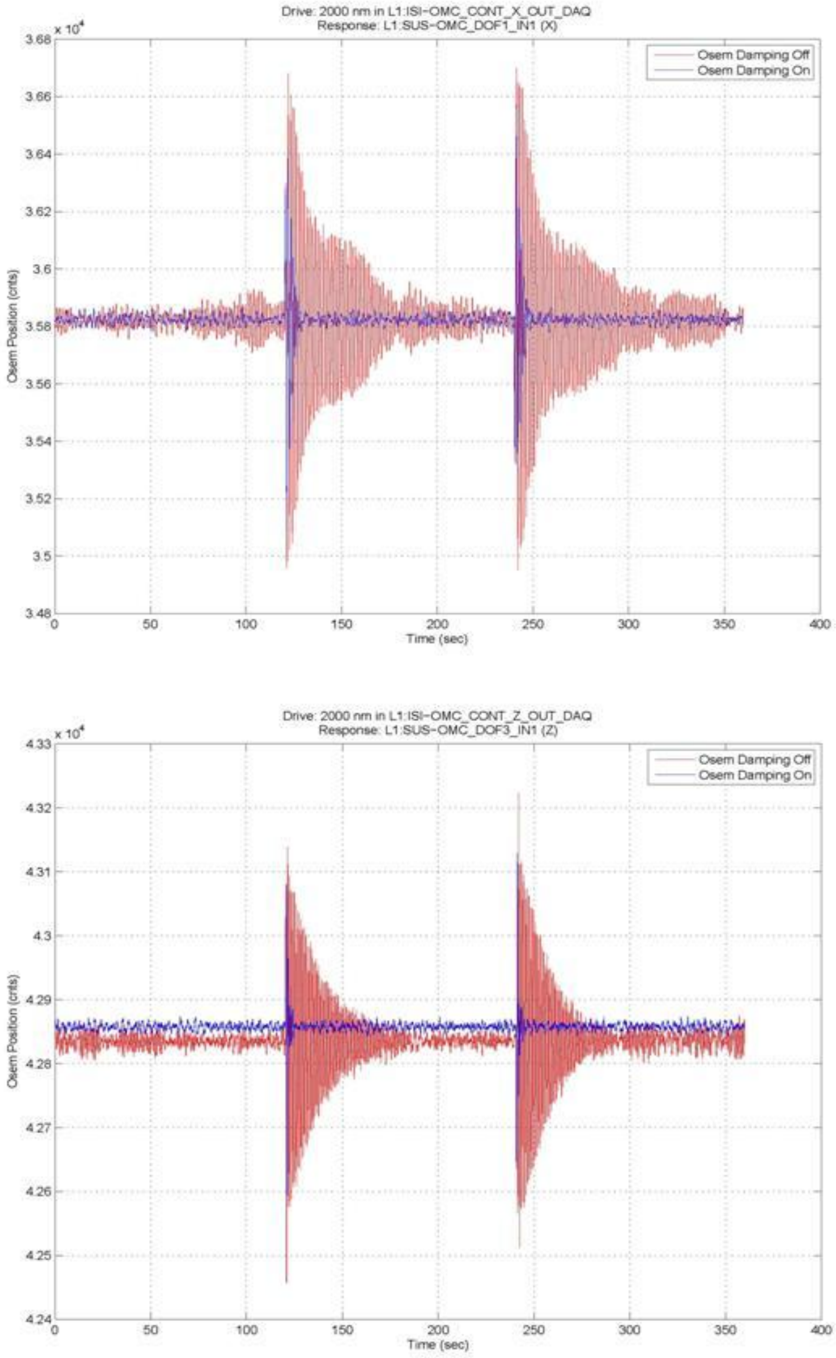

Figure 8. Decay curves for the LLO OMC SUS in the longitudinal (top) and vertical (bottom) directions. The starting points for the two decay curves correspond to when the step input on the HAM-ISI table was switched on and then switched off.

3) The decision has been taken (see E0900023) to nickel plate all blades in Advanced LIGO, to mitigate rust corrosion problems. None of the blades in the two OMC suspensions are nickel plated.)

4) The blades in the LHO OMC suspension did not come within spec and so the lower blades were shot peened to change their shape. The upper blades were deemed close enough to spec to use. Measurements were subsequently made on the shot peened lower blades to check on linearity and deflection and they were deemed acceptable for use. However we do not know about the long term behaviour of blades treated in this way.

5) The LLO and LHO structures are not identical. In particular some holes in the earlier LLO designed were changed to slots in the LHO design. So if we reuse the LLO structure it will require some modest rework.

6) It is intended that some of the electronics will be reused including ADCs, DACs and probably the coil drivers, but the satellite amps will need to be replaced with new ones, since the ones on the present OMC do not have the whitening. The AA can be reused, but the AI will need to be changed to the version that has watchdog capability. The IO chassis and some of the cabling will also be changed.

8 Final design review design checklist

We have taken the checklist given in the guidelines document M050220-09-D page 10 and produced a spreadsheet T090062-v1.xls. For each point on the checklist we have listed the document(s) which address that topic (where such exist).

9 Conclusions

Based on our experiences with bench testing and with the installation and operation of two prototype OMC suspensions at the observatories we believe we have a mature design which satisfies the requirement/specifications set for this suspension. We have assembled a list of lessons learned, E0900049-v1, which will be addressed in the production items.