LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Buoyancy correction for suspensions

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1 Introduction

1.1 Purpose and Scope

When a chamber containing a suspension is pumped down, the loss of buoyancy from the air causes a slight sag of the hanging masses, with implications for OSEM and EQ stop adjustment. The initial version of this document estimates the magnitude for quad TM, CP and ERM chains, updating the calculation first made by Brett for the noise prototype at LASTI. -v2 adds the BS/FM. Later versions will add estimates for other suspension types.

1.2 References

LASTI ilog: http://www.ligo.mit.edu/ilog/pub/ilog.cgi

Brett's LASTI ilog entries of 5/13/09 and 6/29/10

T1100455: Analysis of position/voltage data on a BOSEM

SUS SVN (browser view): https://redoubt.ligo-wa.caltech.edu/websvn/listing.php?repname=sus&

SUS SVN (client view): https://redoubt.ligo-wa.caltech.edu/svn/sus/

M1100256: Suspension Earthquake Stops to be Set at 0.75 mm

D0901346: Advanced LIGO Quadruple Suspension

E1101037: aLIGO BSC ISI/Quad Installation Procedure

D1000392: aLIGO BS/FM MAIN ASSEMBLY

1.3 Version history

1/12/18: -v1. Initial version with analysis for TM, CP and ERM chains.

1/23/12: -v2. Added analysis for glass and metal build BS/FM. Removed counts values where there was no associated OSEM. Added references, especially M1100256.

2 Background

Suspended masses (and other objects) in the open vacuum chambers will experience an upward buoyancy force in proportion to their volume. When a chamber is pumped down, the force due to the air is removed. This turns out to produce a significant sag for the quad suspension, which is vertically soft due to multiple layers of blade springs.

This has the following effects for the quad (the BS/FM is very similar but with only one chain):

1. The LF and RT BOSEMs for the top mass in each chain are attached to the structure and vertically oriented, and will see the drop of the mass directly, as a move away from the working position set in initial adjustment.
2. The F1, F2, F2, and SD BOSEMs for the top mass are attached to the structure and horizontally oriented, and will be de-centered slightly. This is unlikely to be a big problem but they could change their gain slightly, or, if they are poorly centered to begin with, they could be brought to the point of fouling.

3. The BOSEMs and AOSEMs on the upper-intermediate and penultimate masses will be also decentered slightly if the sag is different between the chains (which it turns out it is).
4. All of the masses will move vertically relative to the earthquake stops. This is particularly significant for the lower masses.

3 Theory

The following theory is an update of the calculation used in Brett's LASTI ilog entries of 5/13/09 and 6/29/10.

The LIGO LVEA is kept at around 70F (John Worden). The density of air at this temperature is $\rho_{\mathrm{AIR}} = 1.2$ kg/m^3.

The force on a single mass depends on the volume, which in turn depends on the mass and average density:

$$F_i = \rho_{\mathrm{AIR}} \frac{m_i}{\rho_i} g$$

where $i = 0...3$.

The glass masses are fairly homogeneous and for the density we take the bulk value of 2200 kg/m^3. The metal masses are a composite of different materials, so we take as representative the density of stainless steel, 7900 kg/m^3.

A disappearing buoyancy force at one mass creates sag at all four masses, as the force propagates via the springs. This is conveniently summed up in a compliance matrix, and the net effect at each mass can be calculated by multiplying the vector of forces at the four masses by the compliance matrix to get a vector of sag displacements:

$$\mathbf{S} = \mathbf{C} \cdot \mathbf{F}$$

Mathematica models of the three quad chain types of interest (TM, CP, ERM) are in the following directory of the SUS SVN

`^/trunk/Common/MathematicaModels/QuadLite2Lateral/mark.barton`

The cases of interest are `20111121TMproductionTM`, `20111121TMproductionCP` and `20111121TMproductionERM`.

Because the blade springs are common to all chains, there is a single quad compliance matrix (units in mm/100 g):

	Top	UIM	PM	TM
Top	0.344389	0.344389	0.344389	0.344389
UIM	0.344389	0.643029	0.643029	0.643029
PUM	0.344389	0.643029	0.850089	0.850089
TM	0.344389	0.643029	0.850089	0.864969

The derivation of this is in the SUS SVN at

`…/20111121TMproductionTM/sagcalc/ASUS4XLLateralModelCalcSag.nb`.

The compliance matrix for the BS/FM is

	Top	IM	BS/FM
Top	0.344389	0.344389	0.344389
IM	0.344389	0.643029	0.643029
BS/FM	0.344389	0.643029	0.864969

The derivation is at `^/trunk/Common/MathematicaModels/TripleLite2/mark.barton/20120120bsNW/sagcalc/ASUS3L2ModelCalcSag.nb`. The model used corresponds to Jeff Kissel's production BS/FM model in Matlab at `^/trunk/Common/MatlabTools/TripleModel_Production/bsfmopt_metal.m` (revision 2005 of 1/19/12)

For the BOSEMs, the sensitivity to flag position as a fraction of open light is 1.22 OL/mm (average of three values from T1100455-v2), and BOSEMs will be operated with digital normalization to 30000 counts, for a net sensitivity of 36600 counts/mm.

4 Results

4.1 Test mass chain

parameter set: `mark.barton/20111121TMproductionTM`

	Mass (kg)	Density	Volume (cc)	Buoyancy (g)	Sag (mm)	Sag (counts)
Top	21.999	7900	2.78	3.34	0.17	4221
UIM	21.526	7900	2.72	3.27	0.31	
PUM	39.633	2200	18.02	21.62	0.40	
TM	39.631	2200	18.01	21.62	0.40	

4.2 Compensation plate chain

parameter set: `mark.barton/20111121TMproductionCP`

	Mass (kg)	Density	Volume (cc)	Buoyancy (g)	Sag (mm)	Sag (counts)
Top	22.002	7900	2.79	3.34	0.09	2248
UIM	21.532	7900	2.73	3.27	0.16	
PRM	59.229	7900	7.50	9.00	0.20	
CP	20.039	2200	9.11	10.93	0.20	

4.3 End reaction mass chain

parameter set: `mark.barton/20111121TMproductionERM`

	Mass (kg)	Density	Volume (cc)	Buoyancy (g)	Sag (mm)	Sag (counts)
Top	22.002	7900	2.79	3.34	0.10	2412
UIM	21.532	7900	2.73	3.27	0.17	
PRM	53.536	7900	6.78	8.13	0.22	
ERM	25.19	2200	11.45	13.74	0.22	

4.4 BS/FM metal build (as for one-arm test dummy installation)

We assume densities corresponding to stainless, aluminum and aluminum.

	Mass (kg)	Density	Volume (cc)	Buoyancy (g)	Sag (mm)	Sag (counts)
Top	12.63	7900	1.60	1.92	0.05	1208
IM	13.575	2700	5.03	6.03	0.09	
BS/FM	14.21	2700	5.26	6.32	0.10	

4.5 BS/FM glass build

We assume densities corresponding to stainless, aluminium and fused silica.

	Mass (kg)	Density	Volume (cc)	Buoyancy (g)	Sag (mm)	Sag (counts)
Top	12.63	7900	1.60	1.92	0.05	1330
IM	13.575	2700	5.03	6.03	0.10	
BS/FM	14.21	2200	6.46	7.75	0.11	

5 Installation procedure

1. Check at the output of the OSEMINF MEDM screen and make sure the BOSEMs are normalized to ±15000 counts (with the standard sign convention where negative counts mean entered and positive counts mean retracted).
2. Set the LF and RT BOSEMs physically so that they're negative by about the number of counts in green.
3. Check that the V (vertical) value is positive by about the number of counts in green (i.e., that much less than "1/2 full" on the OSEM_ALIGN speedo display in MEDM).
4. Set the EQ stops so that they will give the 0.75 mm gap called for in M1100256 after the masses have dropped by about the distance in orange. The allowed tolerance is 0.25 mm, so feel free to ignore sag values smaller than that. The priorities are the PUM and TM of the quad main chain.