LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

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LLO ETMY post-welding pitch value: summary, actions & lessons

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1 Introduction

The purpose of this document is to identify the reasons for the significant pitch misalignment seen after the ETMY welding at LLO in November 2013, discuss practical ways to rectify the pitch misalignment and suggest actions to avoid this on future hangs.

2 Background

After the welding of the ETM at LLO it was discovered that the pitch of the test mass with respect to the PUM was ~ 6 mrad[i]. In previous hangs, it had been possible to achieve a differential pitch between these two masses of 2 mrad or less. Three possibilities were raised as to why this hang had a much larger pitch differential than expected.

1. The AR coated surface may have been used as the reference instead of the HR surface during the welding
2. The attachment point of the fibre may have been shifted with respect to the centre of mass of the ETM
3. The fibre lengths may not have all been the same

1) The wedge angle *w*, between the surfaces of this test mass ETM09 is given in the vendor report as 0.07 degrees (1.2 mrad). The mass is aligned such that the wedge is vertical and the thick part is at the bottom of the mass. If the AR side is referenced through the HR side, and the reflected beam is parallel to the beam from the PUM, then the HR surface will be sitting at *n.w (= 1.8 mrad)* to the PUM, where *n* is the refractive index of the ETM[ii]. The mass will be pitched “up” and so the front fibres will be slightly shorter. This would not give a direct change in violin modes, as the difference in length is taken up in the 3 mm stock and not the 400 micron main length of the fibre. There will be a second order effect due to the shift in centre of mass due to the non-zero pitch, this would be ~1 Hz in the violin modes (assuming a d-value of 10 mm[iii]).

2) An asymmetry, front to back, of the suspension points with respect to the centre of mass, due to ear positioning or fibre positioning, will cause the fibres to have different tension. If we assume that the fibres are initially identical, the difference in tension will cause the fibres to stretch different amounts, which leads to an offset in pitch (and roll and yaw). The difference in tension would also manifest itself as differences in violin mode frequencies, and as a torque at the PUM. We do see a difference in violin mode frequencies for the fibres[iv], but we do not see a difference in violin modes for the wires suspending the PUM[v]. This indicates that there is no torque at the PUM, and so that there is nominally equal tension on all the fibres.

3) Differences in the cross-sectional area of the fibres would lead directly to changes in fibre length as a consequence of differential stretch. The fibre stretches by 6.0 mm under full load; the attachment points are 30 mm apart. A differential stretch of 30 microns between front and back fibres would give a pitch of 1 mrad. The important measure for this is the integral of the reciprocal

of the cross-sectional area along the fibre length, but one can get a rough guide simply by looking for systematic differences in fibre diameter. In fact, when the "average centre diameter" was compared with the violin mode frequency, then there was a strong positive inverse correlation. The thicker fibres had a lower violin frequency. The front (HR surface) fibres had a higher frequency, implying they are thinner and therefore stretch more. The mass is therefore pitched "down".

3 Corrective Action

During this investigation we looked back at two previous hangs to see if there was a similar correlation between violin modes and fibre diameter. For these hangs we did not find the same strong correlation, but we did note that the spread in "average diameter" for the fibres from the previous hangs was ~ 5/8 times smaller than for the LLO ETMY. The template for the fibre profiles currently allows the diameter to be visually inspected against the nominal 400 micron diameter. We propose to add a measure to the template that gives a value for the estimated stretch under load, and provide a specification for this. This will allow fibres to be either rejected or to be batched into groups of equal stretch, depending on the outcome of future discussions.

4 Fix on Current Assembly

Let us consider the ETMY again. The mass has a differential pitch due to different fibre lengths front and back. We can correct for this by increasing the length of the back fibres. We can do this with some certainty in the following way[vi]:

We know the relationship between tension on the fibre, stretch length and violin mode frequency. We deliberately stretch the fibre a known amount by applying a tension and measuring the resultant violin mode. We alter the tension until the violin mode corresponds to the stretch we want (for 6 mrad this would be 0.2 mm and about 100 Hz). We then relieve this tension by heating the fibre stock and weld area. When heated, the silica in this region will be pulled slightly thinner until the tension is relieved. The result changes the distance between the attachment points of the fibre without significantly affecting the other properties of the fibre. It is important that the other fibres are not held under high tension during this process or the mass may move in response to that. The actual tension of the two fibres not being acted on is not important as long as it is small. This process does not significantly change the violin mode frequency of the fibres on the free hanging mass as we are only changing the stock region, not the thin flexible main region of the fibre.

Test on this process have shown that it is typically 70% accurate, reducing the offset to below 2mrad, and it can be repeated at least a couple of times without any ill effects.

5 Appendix

Violin mode frequency for LLO ETMY hang, Nov'13 and two previous hangs.

	Violin mode frequency, Hz	"average diameter", microns	Spread in "average diameter"	Spread in frequency
Left front	513.2	412.9	8.6	13.5
Left back	501.1	421.5		
Right front	514.6	414.1		
Right back	503.2	419.0		

LLO Nov'12	ITMX		Spread in "average diameter"	Spread in frequency
FL	513.7	401.7	5.6	5.3
BL	512.5	402.2		
FR	508.6	402.4		
BR	508.4	396.8		

LHO Dec'11	ETMY			
FL	508.8	399.8	5.4	6.7
BL	510.5	396.1		
FR	515.5	400.4		
BR	515.5	395.0		

6 References

[i] https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=9690

[ii] T1000302 “Notes on the quadruple suspension status after welding of the monolithic stage”

[iii] T1000545 “Setting d-values in the Monolithic Suspension”

[iv] https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=9683

[v] https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=9771

[vi] T1100547 “Pitch adjustment of the monolithic after welding”