Review of the requirement for a reaction chain on the BS and FM suspensions in Advanced LIGO, LIGO-T060157-01-K

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1 Update

A few notes have been added to consider whether the large magnets (10 mm long by 10 mm diameter) can be used on the penultimate stage of the beamsplitter (BS). These would be used in conjunction with the 'Birmingham' OSEM bodies. At the time of writing there is some uncertainty regarding the amount of eddy current damping that may be experienced with this OSEM design. It may be necessary to use a different body material for the BS OSEMs. This point is not addressed here. The updates are put in 'update' subsections below.

2 Introduction and references

It has been assumed that, as for the ETM and ITM suspensions, the BS and FM (beamsplitter and folding mirror) suspensions would require a reaction chain to allow low-noise feedback to the PM (penultimate mass) stage. This document reviews and rejects the necessity of this, based on science-mode design requirements.

The BS and FM suspensions are very similar, and have to meet essentially the same requirements so are considered together. They are triple suspensions, with actuation at the top stage – against the table-cloth part of the suspension structure – and the PM stage.

If the reaction chain is not needed there will be obvious savings in design effort, but also increased flexibility to design a stiff support structure within the envelope allowed for the suspensions – e.g. by permitting cross-bracing in the region previously occupied by the reaction chain, or reducing the overall size/mass of the structure.

The PM actuation requirements are not clear at present. It is assumed here that the actuation requirements are the same as for the PMs on the ETM/ITM suspensions (in terms of force and bandwidth). This determines that the actuators consist of initial LIGO style coils, with double-length magnets to give the performance described in T060001-00). The suspensions are lighter than those of the TMs and that will result in slightly larger displacements for the same maximum force.

The key step in making the decision is to evaluate the coupling produced in this actuator due to non-uniform field gradient, see below.

The requirements for the technical noise at the BS and FM optics are given in the Cavity Optics DRD (T01007-03). These are restated below and translated to equivalent requirements at the PM level using a suitable suspension model.

The last ingredient of this decision process is the anticipated motion of the suspension structure due to optical table motion, obtained from E990303-03 as, ideally, $2 \times 10^{-13}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. This is also discussed below.

As usual, with this type of calculation, the isolation increases rapidly above the lower end of the measurement band. Generally the requirement can be satisfied provided performance goal is met at 10 Hz. However, transmissibility peaks at resonances of the support structure could be problematic. This aspect should be checked when the structure design is nearly final.

3 Actuator performance

The actuators are assumed to consist of initial LIGO style coils with double-length magnets (approx 2 mm dia. by 6 mm long). Four of these act longitudinally on each PM. They are designed to be operable with peak force of about 5 mN each, but with a high peak-to-rms ratio. Due to the marionette design of the triple pendulum, there is no need for any DC component on these actuators, indeed the crossover with top stage actuators should be well above 1 Hz.

It is assumed that these could be operated with up to 10 mN *rms* acting on the PM. This is likely to be greater than the normal *rms* force in science mode.

The Mathematica Model 'SweetSpot2.nb', written by Mark Barton for the modelling of such actuators, was used to estimate the maximum gradient of applied force against coil displacement. It was assumed that the coils can be set to within 0.5 mm of the sweet spot. The required range is, additionally, 0.7 mm peak-peak, limited by the shadow-sensors at the top mass. It is then conservative to allow a total pk-pk range of 1.7 mm, and to look for the maximum gradient within that range (as expected it is found at one of the extremes of the range). The result from the model is a change of force with distance of $\approx 30\,\mathrm{m}^{-1}$. Multiplying this by the assumed *rms* force gives the result $\approx 0.3\,\mathrm{Nm}^{-1}$.

3.1 Update

The peak position error of ± 0.85 mm assumed above is large enough that the gradient of the force increases only modestly for the case where the magnet is too far out from the coil. The situation is, of course, worse in the inward direction. The new results are calculated for an offset of 1 mm too far in.

4 Requirements

The key longitudinal displacement noise limit is given in 3.2.3.2 of the DRD as $2 \times 10^{-17}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. Noise due to PM actuation must be at least a factor 10 below that.

A rough estimate of the magnitude of the transfer function from force at the PM to motion of the optic is $10^{-7}\mathrm{mN}^{-1}$ at 10 Hz. N. Robertson confirmed that the current design performs a little better than this. Building in the usual factor of 10 safety, the force-noise limit on the PM is therefore taken to be $\approx 2 \times 10^{-11}\,\mathrm{N}/\sqrt{\mathrm{Hz}}$.

5 Platform motion

The requirement for the longitudinal platform motion is given in E990303-03 as, ideally, $2 \times 10^{-13}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. The point on the structure at which the PM actuators would be mounted could have greater motion due to pitch motion of the optics table, poor SEI performance near 10 Hz or resonances in the structure. Conservatively it seems reasonable to assume something like $5 \times 10^{-13}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ as the expected structure motion in the resonance-free region around 10 Hz, with more margin around the structural resonances.

The structure is likely to have relatively high Q resonances – of order 1000, or higher – at 80 Hz or above. These may be damped through coupling to the SEI or by the addition of damping struts. At 80 Hz the isolation provided by the suspensions against forces at the PM stage is already 4000 times greater than at 10 Hz, so it seems likely that these resonances would not be problematic unless they were of extremely high Q.

6 Main result and conclusion

By taking the actuator performance of section 2, in combination with the force limit in section 3, the tolerable displacement of the actuators is obtained as $6 \times 10^{-11}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$.

Comparing this with the anticipated structure motion from section 4, it is seen that there is an additional margin of at least 120. It is not necessary to have a reaction chain on the BS and FM suspensions.

If necessary the actuators could be strengthened by changing the coils to the larger UIM/Top mass style (Birmingham design) and/or increasing the magnet volume, this matter is left to ISC.

6.1 Update

The large coils and magnets, with the magnet 1 mm closer to the coil than the sweet-spot and an *rms* applied force of 300 mN (as there is no *dc* applied here I took roughly the *rms* of the largest sinusoidal force for a single coil-magnet), leads to a force gradient of about 200 N/m. The platform motion thus leads to a force noise of (not more than) $4 \times 10^{-11}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ – above the allowed noise. Without knowing the waveform of the (deliberately) applied force, it is very difficult to estimate the true extent of the coupling. An estimate of 40 mN for the *rms* force was mentioned in an email from Peter Fritschel. If this figure is taken, the coupling is 4 times smaller than the allowed maximum (which incorporates the usual factor of 10). If the required force can be reduced in science mode, the coupling problem is reduced in proportion.

In conclusion, it appears to be possible to have the requested strong actuation at the BS penultimate stage actuating direct from the suspension structure. Should experience dictate that the required *rms* forces are larger than the 40 mN suggested above, it will be necessary either to ensure that the magnet is positioned closer to the sweet-spot than stated above (which may not be easy even if sensors are fitted as there is no adjustable reaction chain) or to use a dual-coil geometry that gives a larger sweet spot for a modest reduction in actuation force – such arrangements were studied for GEO 600 for test-mass actuation, but in the end replaced by the electrostatic drives – reference not available at present.