Increased strength Advanced LIGO ITM/ETM suspension PM and UIM Actuators LIGO-T060001-00-K

K.A. Strain for ALUK

January 5, 2006

1 Introduction and references

Initial LSC (global control) design by Rana Adhikari and further work by Peter Fritschel, has led to the conclusion that we should strive to design more powerful actuators for the UIM stage of the ITM/ETM suspensions.
See LIGO-T050271-00-D
http://www.its.caltech.edu/ rana/aLIGO/lsc.html
and http://www.its.caltech.edu/ rana/aLIGO/suselecreq.html

The main conclusions from these references are

- UIM unshielded longitudinal dipole strength $\leq 0.11\,\mathrm{Am}^2$
- PM unshielded longitudinal dipole strength $\leq 3.6\,\mathrm{mAm}^2$
- ± 0.5 mrad bias range
- PM rms force 2.5 mN, with sufficient headroom to allow for peaks
- UIM rms force 240 mN, with sufficient headroom to allow for peaks

It is stated that improving the matching of the four actuator magnets on one mass will not help, due to the small-scale variation in the stray fields. In this case the only practical means of allowing stronger magnets would be to place an opposed, matched 'shielding' magnet within a a few cm of each actuator magnet. By this means it should be possible to allow somewhat stronger magnets where necessary.
Notation:-
UIM: Upper Intermediate Mass (2nd top stage)
PM: Penultimate Mass (stage above mirror).

To achieve the desired long-term operation in a 'high noise' state, as defined on the above web pages, requires stronger actuators on the ETM/ITM quad suspensions. An email was circulated suggesting a goal of about 5 N peak force from a set of four UIM actuators, for example, but it is expected that this can be reduced by directing feedback forces to the SEI platforms. The peak figure included a margin of 26 dB above the expected *rms* force. This margin seems generous for commissioning mode. A more practical goal is a peak force of about 2 N, and it is hoped this will be adequate.

It is expected that the peak demand will be on relatively short timescales (up to, say, 10 s, and probably normally much less), in which case it may be acceptable to overload the coils – especially given the large peak-to-*rms* ratio. Although, in principle, we could start designing a new solution from scratch, to expedite progress we explore only relatively minor modifications of the baseline design.

The fundamental limits to magnetic-motor design are magnet strength and power dissipation in the coil. The former is constrained as stated above, but the limits for the latter are less clear. The expected waveform is uncertain and there is not a good estimate of the allowable short term overheating of the coil. As a starting point it is assumed that the dissipation limit could peak at 1 W for of order 10 s provided that the long-term*rms* power remains no more than 100 mW. The metal-bodied UIM coils should have better performance than the ceramic bodied PM coils in this respect.

The baseline OSEM/magnet designs have nominal power dissipation limits of about 0.1 W. There are reports of Initial LIGO OSEM coils surviving *sustained* operation at 400 mA (over 1.6 W), although with unacceptably increased outgassing. Failure is reported to have occurred at about 630 mA. As it is intended to use the same type of wire, it seems wise to restrict the short-term current to about 400 mA to avoid local overheating in the middle windings of a coil.

2 Model

The model employed here is based on the Mathematica model written by Mark Barton for the design of the initial LIGO actuators. Code was added to estimate coil resistance and power dissipation.

3 UIM actuators

The proposed magnets are $\sim 0.3\,\mathrm{Am}^2$ (5 mm long by 10 mm diameter). These and the double-length alternatives are probably both acceptable, as a factor of ~ 6 cancellation should be possible without reducing motor-strength too much (see section 5).[1]

The coil ID and OD are taken to be within the limits set by the present mechanical design – there would be little or no practical advantage gained by breaking this assumption. The ID was therefore taken to be 16 mm and the OD allowed to vary up to 32 mm. The length of the coil was assumed to be adjustable from the starting point 4 mm coil, up to 12 mm, beyond which there is little to gain.[2]

It was assumed that the 'standard' wire would be used. This has 8 mil copper and 10.7 mil total diameter for the assumed heavily coated version (QML grade). There is a gain of around 10%, typically, in moving to HML grade, if other details of coil construction permit. It was felt that thicker wire and higher currents would be impractical from a drive-electronics point of view, and that thinner wire would be less efficient for fixed insulation thickness.

3.1 Selected results (UIM)

A table of magnet and coil dimensions, maximum current for 1 W dissipation and resulting maximum force is given.

[1] Magnet strengths can vary by as much as 30% among different grades and batches of NdFeB, all figures given here are to be read with this in mind.

[2] Approximate metric equivalent dimensions are used here for convenience. Small changes in coil dimensions can be compensated by similar adjustments to current with almost no other effect.

mag length mm	coil length mm	coil depth mm	I max. mA	F max. N	Notes
5	4	8	345	0.23	Note 1
5	8	4	378	0.29	
5	8	8	244	0.29	
5	12	4	310	0.30	
5	12	8	200	0.30	
10	4	8	345	0.39	
10	8	4	378	0.48	
10	8	8	244	0.50	
10	12	4	310	0.51	
10	12	8	200	0.52	

Note 1: this result is close to the baseline coil design with the suggested magnets. The magnets are nearly 3 times as strong as permitted in LIGO-T050271-00-D. The force calculated here is about 2.7 times greater than the figure given there.

The force numbers shown are intended to be accurate to within about 5%, but mainly to be taken as relative indicators of strength at that level, as the absolute strength may vary depending on magnet grade, etc. The results are *per magnet*.

The main effect of changing the OD of the coil is to reduce the current and increase the voltage that must be delivered for a given force. The force obtained for 1 W of heating is not affected significantly. This parameter is, therefore, conveniently used to match the coil to the drive electronics. Note that the change of coil resistance with temperature has been ignored in this calculation.

Increasing the coil length and reducing the current, to keep the power constant, produces a useful increase in efficiency, but most of the benefit arises from the first factor of two increase in length.

For all of the examples given the force is reasonably and similarly constant over at $\sim$ 2 mm range about the maximum. This is probably a result of the ID of the coil being kept constant throughout.

Perfect winding has been assumed in all cases, imperfect winding reduces the number of turns and also the maximum current due to poorer tolerance of local heating.

The largest values shown in the table are quite likely to meet the final expression of the force requirement, provided the longer magnets are acceptable, and that some of the actuation is transferred to the SEI platform.

4 PM actuators

The proposed magnets ($\sim 0.007\,\mathrm{Am}^2$) and even a few times larger magnets can be used, provided that good cancellation can be achieved.

It is proposed to use the initial LIGO OSEM bodies (without sensors) for these actuators, as they are already designed and are insulating (eddy-current damping would be intolerable with an aluminium body). If the sensor components are removed from the OSEMs, it should also be possible to use larger-diameter magnets within the same OSEM body.

4.1 Selected results (PM)

A table of magnet and coil dimensions, maximum current for 1 W dissipation and resulting maximum force is given. Again, convenient metric values have been chosen.

mag dia mm	mag length. mm	coil length mm	coil depth mm	I max. mA	F max. mN	Notes
2	3	4	8	345	4.8	Note 1
2	3	8	8	244	6.2	
2	6	4	8	345	9.0	
2	6	8	8	244	12	
4	3	4	8	345	20	
4	3	8	8	244	25	

Note 1: this result is close to the baseline coil design with the suggested magnets (but not identical due to rounding to metric dimensions). The result for 4 coils at 100 mA would be 5.6 mN, which is a little less than the expected figure.

The suggested power dissipation of 1 W exceeds the safe long-term average for the ceramic OSEMs (for outgassing, not failure).

The 4 mm diameter magnets may be slightly too strong (at $\sim 30\,\mathrm{mAm}^2$, or about 8 times the suggested limit) to meet noise requirements safely, even with a shielding magnet. An intermediate size such as 3 mm diameter by 3 mm long may be chosen if available.

5 Shielding magnets

It seems reasonable to expect that stronger actuator magnets may be used if a second *shielding* magnet is placed nearby but in opposition. This will inevitably reduce the strength of the actuator. The source of important field (the coil) is presumably very much close than the source of unwanted external fields, so it should be possible to arrange the shielding magnet to be close enough to the actuator magnet to cancel the force from stray fields, but still allow nearly the maximum force to be produced by fields from the coil. The graph shown in figure 1 shows how the force from the coil drops off with distance (along the common coil-magnet axis).

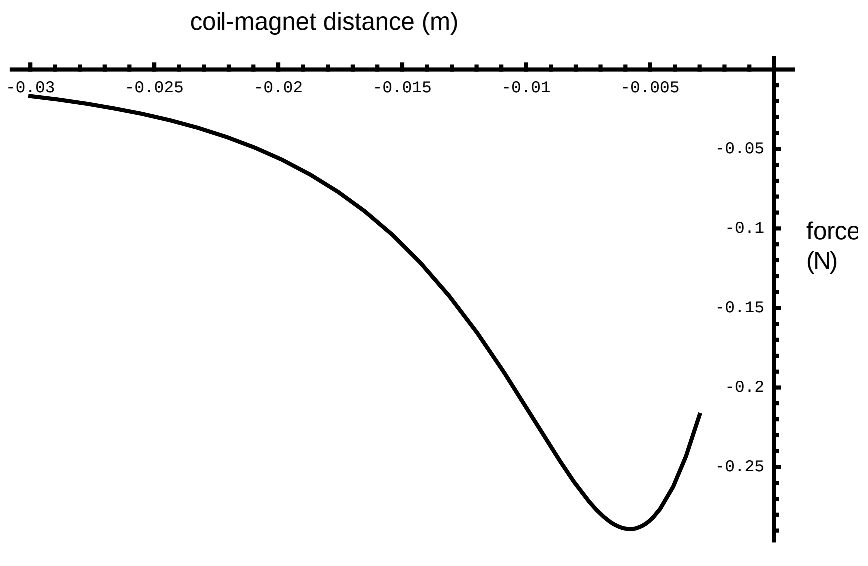

Figure 1: Force as a function of distance along the common coil-magnet axis. The result was calculated for the case of a standard large magnet (5 mm long) and double length coil (8 mm long). It is expected that if a shielding magnet is placed about 30 mm 'behind' the actuator magnet at least 90% of the force from the coil will be retained, and that several-times stronger magnets should be permitted before the interaction with stray fields becomes too great.

6 Conclusions

In response to the request to provide more force, but with no more coupling to external fields, it is necessary to add matched shielding magnets at PM and UIM stages of the quad suspensions. This will allow magnets about twice as strong as proposed in the baseline design to be employed. A factor of around 6 cancellation of the force due to external fields will be needed (in both cases), and is assumed to be possible.

For the PM case, either double-length or larger diameter magnets should provide sufficient force, with the existing coil design (on a ceramic former).

In the case of the UIM, the 10 mm long magnets should provide sufficient force. It is probably worthwhile to at least double the length of the coil.

The drive electronics should be designed with separate long- and short-term current limits. It may be possible to develop a (digital) algorithm that limits the applied power. Another possibility would be to include a temperature sensor within the OSEM head, but this seems complex and expensive. A traditional slow-blow fuse should be fitted in any case.

Note that changes to the coils are not required for the top-mass OSEMs, but they may be changed for convenience.