Meeting Advanced LIGO mode cleaner mirror suspension noise requirements with combinations of active and eddy current local damping.
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Abstract

The local damping solution for the Advanced LIGO quadruple suspensions proposed by the UK team is also applicable to the mode cleaner mirror suspensions. This document assesses the risk associated with both all-active damping and mixed eddy-current plus active damping. The former is found to have a small, probably tolerable risk, while the latter is risk free but requires some revision of the suspension design. It is proposed to accept the risk associated with active damping, but to study the design changes needed should this risk materialize. It is noted, in an appendix, that switching to an all-passive damping approach is not a good option at this stage in the design process.

1 Introduction

The mode cleaner suspensions for Advanced LIGO require to be locally damped, to have local position and angular alignment control, to have local sensing of position and angular alignment and to meet the noise requirements stated in the Cavity-Optics suspension design requirements document T010007-01-1. It is planned to achieve this using a range of techniques, which will also be applied to satisfy similar requirements on the other cavity optics. These techniques are eddy current damping, and active sensing and control based on OSEMS with $10^{-11}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ displacement sensors, digital control, and finally the force feedback using the co-located coil-magnet actuators which are in the OSEMs.

Notes

1. no conclusion arrived at in the present document should be applied to any other Advanced LIGO Cavity Optics suspension – the material is absolutely specific to the mode cleaner suspensions, the arguments do not apply to other cases
2. the mechanical design of early prototype suspensions is at an advanced stage. It was taken as a constraint that the existing layout should be preserved if at all possible
3. the choice of OSEM sensor performance given above is a matter of convenience, alternative approaches based on the use of improved sensors would be possible, at additional cost and with added complexity
4. current versions (as dated) of the mode cleaner suspension dynamical model (MATLAB) and of T010007-01-1 were used to derive all quantitative information in this document
5. it is very unlikely that any modification suspension design would reduce isolation in any degree of freedom by more than a factor of ~ 2 at any frequency above 10 Hz, except at the peak of the highest vertical and roll rigid body suspension modes

2 Review of requirements

Sensing and actuation of the mode-cleaner mirrors in longitudinal, pitch and yaw is required for the purpose of monitoring and global control. See the note given as an appendix below which shows that it is likely to be necessary to apply global forces at the upper mass.

Damping of all (except highest vertical and roll) rigid body suspension modes to give a damping time constant not exceeding 10 s must be provided.

Low noise damping of the same modes must be provided with the option of turning off any channels as (if) required for global control.

The noise requirements are taken from T010007-01-1. They are translated into equivalent sensor noise requirements using the MATLAB/Simulink model of the mode cleaner suspensions (available on the suspension models web page of Mark Barton, the current url is
http://www.ligo.caltech.edu/ mbarton/SUSmodels/index.html)

The basic requirement is that at 10 Hz the longitudinal displacement noise does not exceed $3 \times 10^{-18}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ and the pitch and yaw angular noise does not exceed $3 \times 10^{-15}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$. Roll noise is less critical and is not a design driver as its dampers also damp more sensitive degrees of freedom (vertical, pitch).

3 Evaluating the sensor noise requirements

Translating the above requirements into equivalent sensor noise at the upper stage (using the model with controller as distributed) gives the following derived quantities which apply if active damping with the nominal controller is applied at nominal gain.

The transverse horizontal sensor must not be noisier than $10^{-9}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. This is simple and so the transverse horizontal degree of freedom can be actively damped, without question.

The vertical, yaw and pitch acting sensors (3, 2 and 2 per degree of freedom, respectively) should not be noisier than $5 \times 10^{-12}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ (grouping the 3 similar requirements together and taking the worst case). This cannot be met with the standard sensor and standard controller. For any or all of these degrees of freedom there are two basic approaches: either use eddy current damping or use a modified local control filter which gives at least 4 times lower feedthrough of sensor noise in the frequency range around 10 to 20 Hz (this could be as simple as to permit the local control gain to be reduced by a factor of about 4 when the cavity is locked). The latter option seems to be risk free and simplest to implement.

The requirement for longitudinal becomes $5 \times 10^{-13}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. Eddy current damping would meet this requirement safely. Active damping can probably be made to meet the requirement, but there is definitely some risk associated with this approach. For this reason a little more detail is presented. The longitudinal isolation provided by the suspension depends only on the total length of the suspension, the relative length of the three stages and the relative mass of the three masses. These are very unlikely to change substantially and so the modelled isolation can be taken for granted in this case. Global control does not replace local control in the case of the mode cleaners, as there are 3 mirrors to control with just one length control signal. It is very likely that reduced damping in run mode will be acceptable. The amount of reduction required to allow the proposed OSEM sensor to meet the requirement can be evaluated as there is a direct proportionality between noise and damping (keeping the same controller). The noise must be reduced by a factor of at least 20 and so the damping time would increase, but not exceed 200 s. There is, however, still the possibility of revising the control algorithm to have more gain at low frequency, were damping is most needed, and yet have small gain in the frequency range where noise is most problematic (10 to 20 Hz). One example model allows 30 times reduction in noise with only 3 times reduction in gain – and this is not an optimized design. There is very little risk that 3 times lower damping (in run mode) would cause a problem. It is also very likely that the required algorithm would be developed for other cavity optics suspensions.

4 Conclusion

There are two possible approaches to damp the mode cleaner mirror suspensions.

1. Active damping can be used for all except longitudinal (and, as a side-effect, yaw) damping, with eddy-current damping acting along the x-direction. This would be a very safe approach. OSEMs would be mounted on the opposite face of the suspension to allow longitudinal and yaw control and monitoring.
2. Active damping can be used to damp all degrees of freedom. This has some small risk associated with it as the performance needed is beyond that already demonstrated with active control, even though there are reasonably low risk solutions proposed. [1]

We propose that option 2 be selected.

Appendix

The question arises as to whether it is useful to apply global feedback, and/or to sense for the purpose of monitoring, at the upper stage of these suspensions. The utility of monitoring seems very little provided that there are sensors at the intermediate stage. Acoustic emission affecting the mirror is most easily detected at the mirror or intermediate stage, the proposed sensors would be unlikely to be of use for this purpose at the upper stage.

Global actuation is dynamic range limited. If we allow for a DC range of roughly 1 mm peak to peak it is easy to use the MATLAB model along with performance of typical drive electronics to evaluate the noise resulting from

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[1] The risk to the whole project is smaller as the mode cleaner length noise requirement is very probably over specified, based on very modest expectations for the loop gain in the final frequency stabilization loop.

applying this at any stage. A reasonable figure for the dynamic range of the electronics is 180 dB (snr in a 1 Hz interval at 10 Hz) – requiring, however, post-filtering of the digital output. The three stages of the suspension give ratios of force to displacement transfer function from DC to 10 Hz of -40 dB, -75 dB and -110 dB, respectively for forces applied at the mirror, intermediate and upper stage. A DC range of 0.3 mm rms corresponds to a noise of 220, 255, and 290 dB below this in a 1 Hz bandwidth at 10 Hz when the motion is produced by application of a force to the respective stages. These evaluate to $\approx 3 \times 10^{-15}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ directly at the mirror, $\approx 5 \times 10^{-17}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at the intermediate mass and $\approx 10^{-18}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at the upper stage. Therefore any long range forces must indeed be applied at the upper stage.