Advanced LIGO ITM/ETM suspension: is violin mode damping required? LIGO-T050108-00-K

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1 Introduction and references

The ETM and ITM suspensions of Advanced LIGO include very low loss suspension fibres (round fibres or ribbons of fused silica – henceforth assumed to be ribbons) as described in T010103-04-D. In T050107-01-K it is shown that global control design for steady-state running does not require that the ribbons are damped to reduce the Q of the violin modes – although some damping would certainly simplify control design. Although the Q could be very high (up to of order 10^{10}) sufficient attenuation can be incorporated into the controller, provided the fundamental violin modes fall with in a reasonably narrow band of frequency and are all above 400 Hz (the last is an existing requirement).

The next most obvious driver towards violin mode damping is time to recover from an accidental excitation of the violin mode (e.g. on mis-operation of a servo, or perhaps, mechanical collision of the suspension).

To evaluate the need for damping, and its required properties, it is necessary to determine the following upper limits:

- the excitation that needs to be damped
- the excitation that allows linear operation of global control and hence permits science mode operation
- the allowed down-time due to over-excited violin modes.

These are considered in turn to allow a conclusion to be reached. Note that most of the estimates are intended to be to order of magnitude accuracy.

Several generic approaches to violin mode damping are discussed in the final section.

1.1 Coupling of ribbon and mass

Following the method presented in the PhD. dissertation of Yinglei Huang (Syracuse 1996), it is possible to derive a relationship between violin mode amplitude and mirror motion amplitude arising mainly from the stiffness of the ribbon (and not just the smaller effect due to recoil). The key quantity is, for a suspension with 4 ribbons,

$$r = \pi n \sqrt{\frac{Ebh^3}{3MgL^2}},$$

where E is the Young's modulus of the ribbon ($7 \times 10^{10}\mathrm{Nm}^{-2}$), g is the gravitational acceleration, M is the mirror mass, $b \approx 0.001\,\mathrm{m}$ is the ribbon width, $h \approx 0.0001\,\mathrm{m}$ is the ribbon thickness,

$L \approx 0.6\,\mathrm{m}$ is the ribbon length and n the mode number. For these parameters $r \sim 0.001$ for the fundamental, increasing to a few percent at the top of the ADC bandwidth. For the fundamental this is about 100 times larger than the coupling through recoil alone. (This realisation led to the revision of T050107 to -01 – the low-order violin modes could exceed the background mirror transfer function by as much as $\sim Q/1000 \leq 10^7$.)

2 Accidental excitation: how large?

There are several possible causes for excitation of violin modes, but since nothing is permitted to touch the ribbons directly, these can be classified into collisions of the test mass against stops and instability (or deliberate driving) of a controller with output at the violin mode frequency.

2.1 Collisions

The mirror can move up to $d_\mathrm{m} \sim 1\,\mathrm{mm}$ due to e.g. an earthquake. It then bounces from the stop. During the bounce the ribbon is accelerated and acquires some energy of motion. Although there are many uncertainties, it is very likely that the 'impulses' resulting from collision would lead to ribbon excitation more than the allowed limit of order 10 pm (see below).

2.2 Electronic excitation

To avoid excessive excitation of the violin modes, drive (feedback or test signal) to the TM and PM at around the violin mode frequency should be restricted. Such driving has been the most frequent cause of unwanted excitation of the fibres in GEO 600. As all the signals are produced digitally in LIGO, it is hoped that a protection algorithm can be included to restrict the drive at the violin mode frequencies prior to and when in science mode. Care will be required to ensure that electronic noise in output stages (e.g. of electrostatic drive amplifier in acquisition mode) do not over-excite the violin modes. Also, charges on the ribbons could interact with electronic signals in nearby wiring if not sufficiently shielded.

3 Residual excitation: what is permitted?

The ADC for the main displacement-sensitive channel is assumed to be at least 18-bit (effective), although some headroom must be allowed. The minimum out-of-loop displacement to be sensed is

$$2 \times 10^{-24}/\sqrt{\mathrm{Hz}} \times 4000\,\mathrm{m}/10 = 8 \times 10^{-22}\mathrm{m}/\sqrt{\mathrm{Hz}},$$

where a factor of 10 margin has been included. The noise minimum is about an octave below the violin mode frequency and, therefore, no analogue pre-whitening is assumed.

The available dynamic range of the ADC, assuming a sampling rate of at least 10 kHz, is at least 135 dB in a 1 Hz bandwidth (16-bits, 10 kHz). So the maximum tolerable residual violin mode amplitude at the test mass is about $\mathbf{4 \times 10^{-15}}$ m. The corresponding motion of the ribbon is about 4 pm. This is expected to be comfortably above the thermal noise (and is nearly 3 orders of magnitude above thermal noise estimated in a model neglecting fibre stiffness).

4 Decay time: how long?

The natural decay time (constant) of the violin modes could be as high as $\sim 3 \times 10^9$ cycles, 8×10^6 s or 3 months (although it will probably be much shorter due to inevitable coupling with lossy parts of the suspension). This essentially guarantees that, if the ribbons are *ever* excited beyond the limit found in the previous section additional damping is required to recover. Such excitation is likely to happen so damping is needed.

Assuming that excitation of the ribbons will be a reasonably rare event (daily or less frequent), the tolerable decay time is as much as a few hundred seconds, giving an upper limit to the Q of $\sim 10^6$. This fits well with experience on GEO 600 where $\sim 600\,\mathrm{Hz}$ violin modes with $Q \sim 10^6$ affect detector performance for less than one hour after considerable excitation.

5 Means of damping

The following options require to be explored

- ribbon coatings – not necessarily the Teflon used in GEO 600, risk is unwanted damping at low frequency and weakening of the ribbons
- passive (tuned) dampers on the penultimate masses – requires design work
- active damping sensing either penultimate mass or ribbons, actuating penultimate mass or ribbons

The technique applied in GEO 600 is coating with Teflon. This is not immediately recommended for Advanced LIGO because it is a risky process and hard to control; there is thought to be continuous mass loss observed in GEO, and it may add vertical thermal noise if too much material is applied. Other options for coating very small lengths of the ribbon should be considered. This technique has the major advantage of being able to be optimised to correctly damp all modes, by choice of which sections of ribbon to coat.

Passive tuned-damping at the penultimate mass is attractive, but there are many design issues to be considered before it is seen to be practical. An advantage is that there is very little risk of performance loss or of damage to ribbons. It may be complicated to arrange damping of sufficient modes.

With active control the actuation is most obviously done via the coil-magnet actuators on the penultimate mass (provided it can be shown to be acceptable to actuate the mass rather than the individual ribbons). Individual actuators on the ribbons make control simpler (π less phase lag, smaller forces needed, and access to individual ribbons) but the system complexity increases significantly mainly due to the extra wiring needed.

Sensing requires an auxiliary sensor, which could sense the penultimate mass (or mirror) position or the ribbons directly (sensing the PM may be better as extra equipment is out of the way of the main beam and there is less phase shift due to the suspension). Direct sensing of the ribbons has the advantage that the motion is ~ 1000 times larger (for the fundamental), but the disadvantages are that it could be difficult to align the sensor to the ribbons, and wiring becomes complex.

Each of these methods requires urgent attention to determine which is/are practicable.