# Advanced LIGO ITM/ETM suspension violin modes, operation and control, addendum to T050267-01-K
# LIGO-T060094-00-K

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The aim is to document a few details that were left out of T050267-01. These include, consideration of using the LSC loop to cool violin modes in lock, checking that the PM actuators are capable of delivering the damping forces out of lock, and a closer study of the noise requirements for the VM sensors.

To summarise: depending on the details of the acquisition mode LSC, it is likely that too much excitation of the VMs would lead to saturation that could interfere with locking. Depending on noise levels in that mode, it may be difficult to cool the VMs only in lock, and so an independent damping system is proposed. The main extra requirement for these damping loops is sufficiently low noise sensing (one damping loop per ribbon would be needed).

TM – test mass.
PM – penultimate mass.
ESD – electrostatic drive.
VM – violin mode.
LSC – length sensing and control.
IFO – interferometer.

## 1 Damping the violin modes with modified LSC loops

In principle damping using modified LSC loops should be possible, but a concern arises from experience at GEO 600.

The transfer function from longitudinal force applied to the GEO 600 mirrors to longitudinal displacement (i.e. from ESDs to IFO differential displacement signal) shows features, around some of the violin modes, that would make damping them difficult.

With a simple, 1-dimensional model of the lowest stage of the suspension, the order of poles and zeros in the transfer function, ignoring suspension poles, would be expected to be $z-p-z-p-$ each letter representing a complex pair – in order of increasing frequency. In this case the system is easy to control, as the phase of the transfer function is $-\pi, 0, -\pi, 0, -\pi$, with the transitions at the poles and zeros listed. This is, indeed, observed for several of the 8 modes that were measured (those associated with the two electrostatically-actuated mirrors in GEO 600).

In other cases, however, the transfer function shows the order of poles and zeros to be $z-p-p-z$ and the phase is then $-\pi, 0, -\pi, -2\pi, -\pi$, which is effectively uncontrollable, with gain, around the second pair of poles.

The GEO 600 fibres are observed to be slightly elliptical in section and are also twisted (the major axis rotates along the length of the fibre).

Although there has not been a complete quantitative analysis, this effect could arise due to the twists in the fibres (this is the simplest explanation that was qualitatively verified using a simple, two-dimensional MATLAB model).

If indeed the twist is necessary to create the inconvenient pole-zero ordering, this problem will not occur with ribbons as the construction method does not allow significant twisting. It will not, however, be easy to confirm this until the noise-prototype is tested. Early measurement of the appropriate transfer function is encouraged.

## 2 PM actuator strength and VM damping

The model described in the earlier note was used to estimate the maximum violin mode amplitude which could be damped within the range of the PM actuators. The appropriate transfer functions were calculated and the conclusion was that the force requirement is of order 3 N/nm motion of the TM due to the VM (a mode near 1.2 kHz was taken as typical). As we can allocate of order 1 mN to this task, TM motion of order 0.3 pm (or violin mode amplitudes of order 30 nm) can be accommodated.

It is understood that de-emphasis filters in the PM electronics will be switchable, and so the practical limit to the available force at high frequencies is actuator-coil inductance. This is not expected to be a problem.

## 3 Closer look at VM sensor noise requirements

The noise from VM sensors will feed through the 4 controllers, be summed together, and be applied to the suspension at the PM. The controllers may include relatively narrow filters around each violin mode, so as to avoid the need for broadband gain. Alternatively a flat transfer function with 6 poles of high pass at about 100 Hz would also prevent sensor noise from degrading system performance below the frequency of peak sensitivity. The former approach was taken in the work discussed here.

The response from one sensor to the TM (via controller and PM) was estimated. With 4 sensors, having uncorrelated noise, the noise at the TM would be twice as large. The transfer function from sensor noise to TM displacement reached a peak of -110 dB at the first violin mode frequency, with the damping set to give $Q \sim 3 \times 10^6$. Since the $Q$ a scales with gain, a sensor with $10^{-10}\mathrm{m}/\sqrt{\mathrm{Hz}}$ noise would result in a displacement a little less than $10^{-17}$m *rms* at the TM.

The violin modes should be able to be reduced to a level that does not saturate the ADCs of the LSC low-noise loop. The frequency of the first set of violin modes is about an octave above the frequency of peak sensitivity. It is, therefore, assumed that no whitening of the response is possible to give larger range at the violin modes. [1] It will be necessary to cope with the motion due to 4 sets (4 TMs) of 4 ribbons, so 16 ribbons. Probably the first 3 or 4 modes will contribute significantly to the ADC input signal. If we allow 64 modes of approximately equal amplitude and no particular phase relationship, the voltage will spike up to about 64 times the amplitude of each mode. If the ADC is to continue to operate without saturation, we should allow a factor of several hundred between the amplitude of a single mode and the input range of the ADC. A factor of 1000 is taken for safety, and the minimum anticipated ADC performance is assumed.

The ADC noise is taken to be equal to 10% of the peak system displacement sensitivity so it should not exceed an equivalent displacement noise of $\sim 10^{-21}\mathrm{m}/\sqrt{\mathrm{Hz}}$. The sampling rate is

[1] The signal response of the detector will fall (in displacement terms) above 1 kHz, even if H2 is in narrowband mode. Thus the higher modes are automatically de-emphasised at the input to the ADC, unless too much pre-emphasis is added to boost the shot noise at higher frequency.

taken to be 16 kHz, and so the 1 Hz dynamic range is around 145 dB, or nearly $2 \times 10^7$. Allocating about 0.1% of this range for each violin mode requires that the motion from each mode should be $\leq 2 \times 10^{-17}$ m *rms*. The equivalent sensor-noise (see above for the relationship) is about $2 \times 10^{-10}\mathrm{m}/\sqrt{\mathrm{Hz}}$, which should be taken as the requirement.
In summary, a reasonable performance target for violin mode damping sensors is $10^{-10}\mathrm{m}/\sqrt{\mathrm{Hz}}$.