The Use of Steel Wires for the Advanced LIGO Modecleaner Suspensions

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11th January 2006
LIGO #: T060008-00-R

1. Introduction

The baseline design for the suspensions for the modecleaner (MC) mirrors in Advanced LIGO is to use a triple pendulum with silica fibres in the final stage to meet the noise requirements, as presented in the "Advanced LIGO Suspension System Conceptual Design", T010103-04-D. At a meeting in Caltech (11th July 2005) to discuss the HAM requirements, NAR gave a presentation: "Review of HAM Suspension Designs for Advanced LIGO", G050321-00-R in which the suspension thermal noise curves for the MC using silica fibres and steel wires were shown, see figure 1 below. As was noted in the conceptual design, silica fibres meet the requirement of 3 x 10^{-17} m/$\sqrt{}$ Hz at 10 Hz with a large safety margin, except for a narrow peak at the highest vertical mode. Steel wires also meet the requirement using a larger stress value. For a conservative design we had advocated the use of silica in the MC suspension.

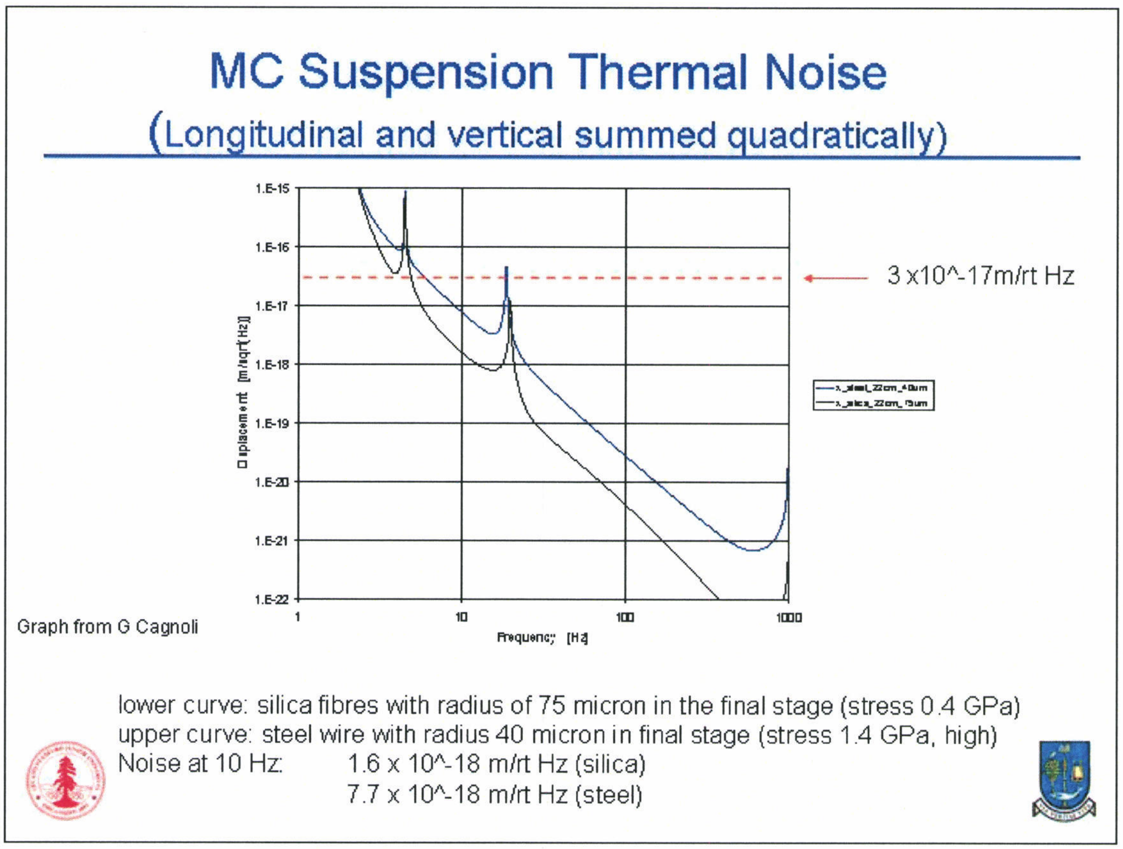

Figure 1. Suspension thermal noise estimates for Adv. LIGO modecleaner suspension. Slide 6 from G050321-00-R.

2. Discussion at HAM requirements meeting, and subsequent considerations.

At the HAM meeting Peter Fritschel presented a review of the arguments used to reach the current noise requirements for the MC optics (see link from Adv LIGO systems meeting page http://www.ligo.caltech.edu/~coyne/AL/SYS/default.htm, for meeting on 11-13 July 2005). The current requirement is set from considering the frequency stability required and the possible loop gain. He concluded that it appears the MC frequency stability requirement could be relaxed by 1 to 2 orders of magnitude to around $\sim 10^{-15}$ m/√Hz at 10 Hz. Several issues need further checking including beam jitter due to MC noise and sensitivity to power and signal recycling mirror motion, and considerations on such issues are currently underway.

As a result of these discussions it was proposed that we reconsider the use of steel wires for the MC suspension. There are clear advantages to using steel rather than silica from considerations of manufacture, assembly and handling of the suspensions. We note two further advantages for operation of the modecleaner. Firstly the quality factor of the violin mode resonances will be reduced by at least two orders of magnitude, therefore easing notch requirements in control loops. Secondly if matching of violin modes is required this should be easier with steel due to easier control of the tolerances on wire diameter. We also note that the recycling mirrors (RM) (which are also HAM suspensions) are already planned to be on wire suspensions, since their noise requirement is almost an order of magnitude relaxed from that of the MCs. Thus one area which might need further development – namely the design of suitable wire break-offs on the optics - will be addressed anyway in the development of the RM steel wire suspensions

It was noted that in the steel wire suspension used for the noise estimate in figure 1 a large stress was assumed in the wires, a factor of ~2 above that used in Initial LIGO. We now consider wires a factor of ~√2 larger in radius, to give a stress of 0.7 GPa, the same as that currently used. The

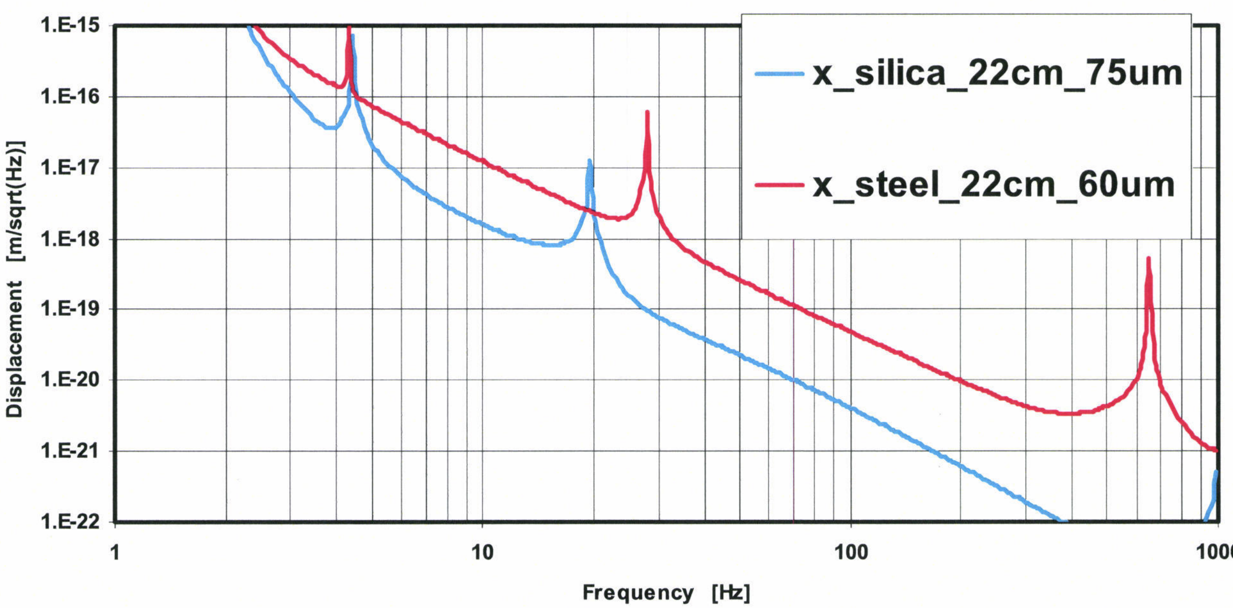

Figure 2. Suspension thermal noise estimates for Adv. LIGO modecleaner suspension. The noise level at 10 Hz for the steel wire (of radius 60 micron) is 1.2 x 10^{-17} m/√ Hz. (Data from G Cagnoli)

estimated suspension thermal noise using the baseline silica fibres and using this revised radius of steel wires is shown in figure 2.

The estimated noise level using the revised wire radius is 1.2×10^{-17} m/√ Hz at 10 Hz, where this value is a quadratic sum of vertical and longitudinal thermal noise. Allowing for no change in the baseline requirement (see T010007-02), where longitudinal plus vertical noise has to be no greater than $3\sqrt{2} \times 10^{-17}$ m/√ Hz = 4.2×10^{-17} m/√Hz (assuming 0.001 vertical to longitudinal coupling), the estimated level appears to be acceptable, with a safety factor of ~3.5. It should be noted that the current baseline requirement is the noise from *all* sources, so we also need to consider the seismic noise contribution. However on current estimates, assuming the isolation platform requirement is met, the seismic noise is well below the baseline number, and thus the quadrature sum is dominated by the thermal noise contribution. Thus a steel wire suspension comfortably meets the current requirement, assuming the noise estimation is valid. If the requirement is relaxed, the thermal noise level is well below the possible new requirement alluded to above of $\sim 10^{-15}$ m/√ Hz.

3. Loss value used in modeling

In the suspension thermal noise model used to produce the graphs shown in figures 1 and 2, the material loss assumed for steel wires ϕ_{mat} is taken to be 2×10^{-4}. This is consistent with the number for C85 steel measured by Cagnoli et al (Phys Lett A **255**, 1999, pp 230-235), and also more recently for the LIGO 1 wires by Penn and Harry (as reported on the SWG elog, entry 79). The question has been raised as to whether the noise performance shown in the graphs above, based on this value of ϕ_{mat}, can be achieved in practice. An idea of what can be achieved for a similar stress level can be deduced from the measured Q values of the violin modes of the steel wires in the current LIGO suspensions. The highest values measured for the fundamental mode are around 1.5×10^5. From initial considerations this Q appeared to be low compared to what one might expect if ϕ_{mat} is taken to be 2×10^{-4} and the dilution effect is as expected. However it was noted that the thermoelastic peak is at a few hundred hertz for the particular parameters in initial LIGO. A Q of 1.5×10^5 implies a total wire loss of 1.3×10^{-3}, close to the expected value from structural damping at the level above plus thermoelastic damping (ref "Enhancements to the LIGO S5 Detectors", Fritschel et al, T050252-00-1). Thus the observations from Initial LIGO do not preclude that one could obtain suspension thermal noise levels for the modecleaner as estimated.

We note that there is considerable variation seen in the violin mode Qs (see "Suspension Thermal Noise in Initial LIGO". G Harry, G050113) and that other factors such as clamp losses or losses due to rubbing of the wire under the mass may be playing a part in some cases. We consider the implications of taking a value for the total effective loss of 2×10^{-3} (excluding thermoelastic), based on those observations (ref. e-mail from G Harry, 2 Nov 2005). This value is ten times larger than the known material loss. Since the displacement due to suspension thermal noise varies as $\sqrt{\phi}$, such a value of ϕ would raise the displacement noise by $\sqrt{10}$ or ~3 assuming ϕ is constant with frequency (which is a conservative assumption, since clamp or rubbing losses might be viscous in nature, and when extrapolating to lower frequency the effect of such losses would be less). Such a loss takes the estimated noise to around 4×10^{-17} m/√Hz, essentially at the current baseline requirement at 10 Hz.

4. Thermal Noise from Pitch

We should also check that thermal noise associated with the pitch mode is also within requirements if a steel wire suspension is used. We note that in the current design requirements document (T010007-02) the pitch noise requirement is called out separately from longitudinal noise, with a value of 3×10^{-14} rad/√ Hz at 10 Hz. We have carried out an estimate of the pitch thermal noise by assuming it is dominated by the final stage suspension, and that the restoring force is dominated by the extension of the wires, so that bending losses can be neglected. Using the following parameters for the final stage suspension, silica mass of 7.5 cm radius by 7.5 cm thick on 4 wires each 60 micron radius, separated in the longitudinal direction by 10 mm, giving an uncoupled pitch frequency of 2.2 Hz, and using $\phi_{mat} = 2 \times 10^{-4}$, we estimate a noise level of 1.1×10^{-14} rad/√ Hz at 10 Hz. Thus the safety factor by which the estimated noise is below the requirement for this value of ϕ_{mat} is similar to the case for the longitudinal and vertical thermal noise.

5. Conclusion

The suspension thermal noise estimate for a modecleaner suspension on steel wires appears to satisfy the existing baseline noise requirement at 10 Hz and above. Taking the steel wire material loss factor to be 2×10^{-4}, as measured by Cagnoli et al, the estimated suspension thermal noise limit lies a factor of ~ 3 below the noise requirement. If we use a value for loss factor ten times larger (2×10^{-3}) the estimated suspension thermal noise lies essentially at the current noise requirement. Since the use of steel wires has several advantages over using silica fibres we therefore propose that the baseline choice of suspension material is changed to steel.