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Suspension loss in Advanced gravitational wave detectors

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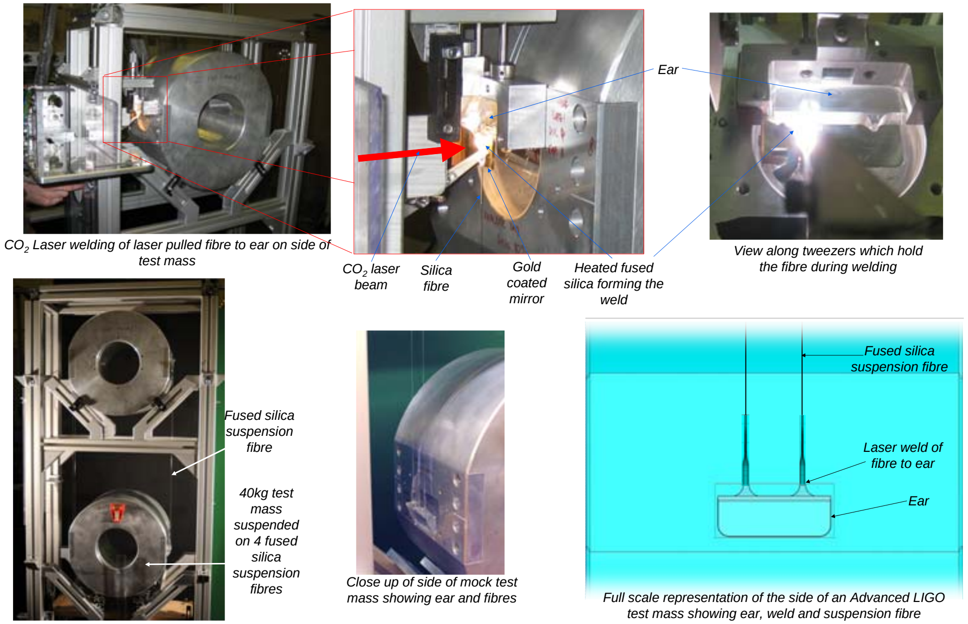
Introduction

Quasi-monolithic mirror suspension technology was developed for the GEO600 interferometric gravitational wave detector to minimise mechanical dissipation (and therefore thermal noise) in the test mass suspensions used to isolate the mirrors from seismic noise. Fused silica attachments ("ears") are silicate bonded to the sides of the silica test masses to provide weld points onto which circular cross section silica fibres can be welded, to create a monolithic silica stage. The future Advanced LIGO detectors will employ ultra-low-loss quasi-monolithic fused silica suspensions developed from those pioneered in GEO600, and with careful optimisation of fibre geometry, mechanical dissipation can be optimised to minimise suspension thermal noise in the 40 kg test mass mirrors.

Glasgow Advanced LIGO monolithic test suspension

The first full scale mock monolithic test suspension has recently been fabricated and successfully hung on the first attempt. This employed the fabrication and installation techniques that will be used to construct the final Advanced LIGO inner and end test mass suspensions. These techniques include CO_2 laser pulling of 400μm diameter suspension fibres and CO_2 laser welding of the fibres onto the fused silica attachment ""ears" using gold coated mirrors, as shown in Figure 1 below.



CO_2 Laser welding of laser pulled fibre to ear on side of test mass

View along tweezers which hold the fibre during welding

Close up of side of mock test mass showing ear and fibres

Full scale representation of the side of an Advanced LIGO test mass showing ear, weld and suspension fibre

Figure 1. *Aspects of mock monolithic test hang including attachment ears, fused silica fibres and CO_2 laser welding*

Optimised suspension design

The mechanical loss of a pendulum suspension, $\phi_{\text{pendulum}}(\omega)$ can be shown to be [1]:

$$\phi_{\text{pendulum}}(\omega) \approx \phi_{\text{fibre}}(\omega)\frac{k_{\text{fibre}}}{k_{\text{gravity}}} \qquad \text{with} \qquad \frac{k_{\text{gravity}}}{k_{\text{fibre}}} = \frac{\frac{mg}{l}}{\frac{\sqrt{FYI}}{2l^2}} = \frac{2mgl}{\sqrt{FYI}} \approx D$$

i.e. the ratio of the gravitational spring constant $k_{gravity}$ to the elastic spring constant of the suspension fibre k_{fibre} is the pendulum dilution factor *D*. To reduce suspension thermal noise, $\phi_{\text{pendulum}}(\omega)$, $\phi_{\text{fibre}}(\omega)$, should be minimised. $\phi_{\text{fibre}}(\omega)$, can be expressed as the sum of three loss components – a frequency dependent bulk material loss $\phi_{\text{bulk}}(\omega)$ [2], a frequency independent component fibre surface loss ϕ_{surface} [3] and a frequency dependent thermoelastic loss component. $\phi_{\text{thermoelastic}}(\omega)$ [4].

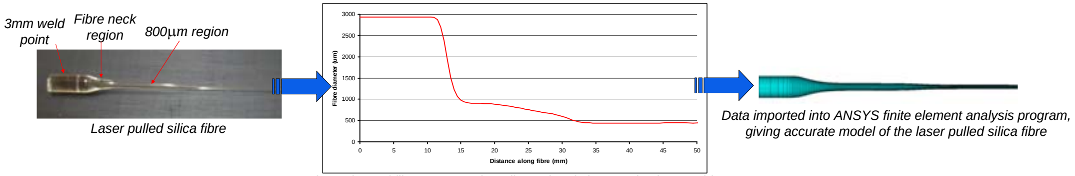
References

[1]P. R. Saulson, Physical Review D 42, 2437 (1990).
[2] S. D. Penn, Physics Letters A **352**, 3 (2006).
[3] A. Gretarsson, Review of Scientific Instruments 70 (1999)
[4] G. Cagnoli, P. Willems, Physical Review B 65 (2002).
[5] A. Gretarsson, Physics Letters A 270 (2000).
[6] P. Fritschel, "Advanced LIGO Systems Design", LIGO Document T010075, (2001) .

$$\underbrace{\phi_{\text{thermoelastic}}(\omega) = \frac{YT}{\rho C}\left(\alpha - \sigma_o\frac{\beta}{Y}\right)^2\left(\frac{\omega\tau}{1+(\omega\tau)^2}\right)}_{\text{Thermoelastic loss (dominant)}} \qquad \underbrace{\phi_{\text{surface}} = \frac{8.53h\phi_s}{d}}_{\text{Surface loss}} \qquad \underbrace{\phi_{\text{bulk}} = 7.6\times10^{-10} f^{0.77}}_{\text{Bulk loss (negligible for thin fibres)}}$$

The dominant loss in thin suspension fibres at the frequencies of interest is thermoelastic loss [5], which results from local spontaneous temperature fluctuations in the fibres, causing heat flow across the temperature gradient on some timescale τ, and subsequently bending to occur in the fibre due to it's thermal expansion coefficient, resulting in displacement noise in the detector. For fused silica the thermal elastic coefficient $\beta = \frac{1}{Y}\frac{dY}{dT}$ (where Y is the Young's Modulus) has a value which is positive [4], meaning that thermoelastic loss can be reduced by application of an appropriate (tensile) static stress σ_o, and in principle nulled entirely when $\sigma_o = \frac{\alpha Y}{\beta}$. For an Advanced LIGO 40 kg mass this nulling occurs for a fibre diameter of 800μm, so fibres are pulled with ends of approximately this diameter to minimise the thermoelastic loss. The central section of the fibre is then fabricated to be ~400 μm diameter to keep the vertical bounce frequency below 10 Hz as per the Advanced LIGO specification [6].

Current fibre production methods pull fibres from heated fused silica rods of larger cross section. The fibre ends therefore have a tapered "neck" section, which provides a convenient end-geometry for welding to the "ears" bonded to the silica test mass. Typically, this neck section is between 5 and 10 mm in length. The neck shapes are measured on a dimensional characterisation machine and the shape profile used to construct a finite element model of the fibre.



Laser pulled silica fibre

Data imported into ANSYS finite element analysis program, giving accurate model of the laser pulled silica fibre

Dimensions of fibre measured on dimensional characterisation machine

Figure 2. *Process used in creating a finite element model of the fused silica suspension fibres used in the mock test suspension*

Finite element models and projected mechanical loss

The finite element model of the fibre can then be used to construct a full model of the lower-stage suspension as shown in Figure 3. By simulating the distortion associated with the pendulum mode, the elastic energy distribution in the fibres and the pendulum mode dilution *D* can be obtained. The energy distribution can then be combined with the appropriate $\phi_{\text{bulk}}(\omega), \phi_{\text{surface}}$ and $\phi_{\text{thermoelastic}}(\omega)$ values for each increment along the fibre in order to evaluate the overall mechanical loss of the suspension, as shown in Figure 4.

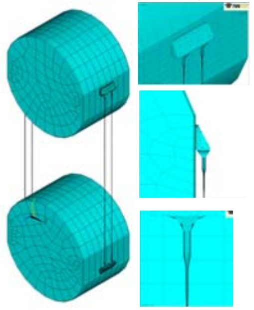


Figure 3. *Finite element model of mock monolithic test suspension*

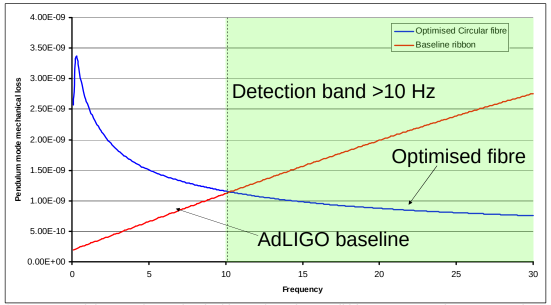


Figure 4. *Pendulum mode mechanical loss of mock monolithic test suspension compared to the original non-optimised ribbon fibres original proposed for Advanced LIGO*

Conclusion

The mechanical loss of the optimised fibre is lower than the baseline Advanced LIGO ribbon design in the detection band of frequencies greater than 10Hz, resulting in lower overall thermal noise than required for the baseling design.

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