Fused silica suspension for the Virgo optics: status and perspectives

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Abstract. Thermal noise in mirror suspension wires is the main limit to the low-frequency sensitivity of interferometric gravitational wave detectors. In order to minimize the pendulum thermal noise a monolithic design, using a low dissipation material, is proposed for Virgo. High mechanical Qs and high breaking strengths have been obtained for monolithic fused silica fibers. A low dissipation and high strength bonding technique using Potassium Silicate Bonding is proposed.

Submitted to: *CQG*

PACS numbers: 43.40.Cw, 62.40.+i, 05.40.-a, 04.80.Nn

1. Introduction

Thermal noise due to the fluctuation of the suspension last stage in the pendulum mode is expected [1] to dominate the Virgo sensitivity in the $5 \div 50$Hz range.

The current suspension solution for a Virgo mirror [2] consists of a $m \simeq 21$ kg cylinder of fused silica, 35cm across and about 10cm thick, suspended in a cradle formed by two parallel wire loops hanging 5cm apart. The effective length of the resulting pendulum is about $L_w = 70$cm. The wires are made of C85 harmonic steel and their diameter is $d_w = 0.2$mm [3]. Four BK7 (borosilicate crown optical glass) prisms are inserted as spacers between the mirror lateral surface and the suspension wires.

For the pendulum mode, it is possible to model the suspension as an ideal oscillator and to use a structure dumping model (i.e. $\phi(\omega) \simeq const$) for the internal dissipation in the oscillator [4].The oscillator loss angle has three components:

$$\phi(\omega) = \phi_w + \phi_e + \phi_{th}(\omega) \qquad (1)$$

where ϕ_w is the loss angle due to the wire material itself, ϕ_e is the excess loss angle due to parasitic dissipation processes like the residual clamping losses [5] and $\phi_{th}(\omega)$ is the thermoelastic contribution [3, 6] to the dissipation. The horizontal displacement power spectrum, at frequency higher than the resonance frequencies, is due to two contributions, the first is the horizontal component and the second is the vertical one which is coupled to the first at least by θ_0, the angle given by the Earth curvature (in Virgo $\theta_0 = 1.35 \times 10^{-4}$).:

$$|X_h(\omega)|^2 \simeq \frac{4k_BT}{\omega^5} g \cdot \left\{ \frac{1}{L_w^2}\sqrt{\frac{Eg}{4\pi nm}} + \theta_0^2 \frac{E}{mL_w} \right\} \cdot \frac{\phi(\omega)}{C_sB} \tag{2}$$

where E is the Young's modulus of the suspension wire material, n is the number of suspension wires (in Virgo $n = 4$), B is the tensile breaking strength (in Pascal) of the wire material and C_s is a safety factor ($C_s < 1$) that express the percentage of the breaking stress at wich the wire is loaded.

From equation 2 is evident the importance of the minimization of the ratio $\frac{\phi(\omega)}{C_sB}$. The optimal material to realize the mirror suspension should be a low dissipation material with a high and reliable (C_s not too small) breaking strength. In order to explore different geometries and materials we performed a wide experimental activity whose main features and results are summarized below.

2. Experimental apparatus

The first apparatus to be described is the machine realized to produce fused silica fibers with large heads. It consists of two vertically sliding frames, that pull a fiber starting from a 5mm diameter synthetic fused silica rod. The rod is melted in a relatively small region using a concentric crown of flames. The flames are produced from very pure oxygen and hydrogen gas. The fibers produced with this technique have been geometrically characterized with a computerized microscope that reads the fiber profile along its entire length. The fiber presents two large head connected to the central part at constant diameter through two tapers. The taper shape and the central wire diameter are related to the length of the part of the rod melted by the flames and to the pulling speed. The current version of the production machine, with a simple manual control, is able to produce wires of the Virgo expected length (about 70cm) with an error of 0.5cm.

A different set-up is used to measure the breaking strength of the fused silica fibers. It has been noted that scratches on the fiber surface can reduce the breaking strength by more than one order of magnitude. Since it is extremly important to avoid any contact between the fiber and any hard surface during breaking strength measurement or mirror suspension, a breaking strength measurement set-up has been realized directly in the production machine itself.

The experimental apparatus used for the measurement of the loss angle has been already described in a previous article [3]. Some improvement has been obtained in the recoil losses reduction and in the read-out noise.

Our sample wires are clamped vertically and left to hang freely. The suspended wire vibrations are excited by an electrostatic actuator. The resulting motion is read through a shadow-meter. The ringdown of the i^{th} mode is acquired and the corresponding mechanical quality factor is measured online by measuring the decay time τ_i.

The last step in order to realize a monolithic suspension, once the fiber is produced, is to attach the fiber head to the mirror. It is pratically impossible to hot weld the fiber directly to the mirror, because of the differences in the heat capacity of the two parts to be welded. For this reason an intermediate step must be performed; a small fused silica appendix, so-called *ear*, to which the fiber will be welded, is attached to the mirror. This *ear* will be attached to a flat strip machined on the lateral surface of the Virgo mirror. The bonding technique to “glue” the *ear* to the mirror is a hydroxide catalysed hydration-dehydration chemical process called *silicate bonding*. The strength of this bonding technique must be enough to safely support the suspended mirror. For this reason a test bench has been realised to measure the strength of the bonding in operative condition. In the test bench, two small cylindric fused silica samples, attached by silicate bonding, can be stressed with a screw that applies a progressive force at about 5 mm away the bonding surfaces in such a way that a large torsion is applied together with a shear stress. The applied stress is measured through a load cell inserted between the screw and the cylinder lateral surface. A force of several hundreds of newtons can be exerted with this device.

3. Experimental Results

Since the strength of fused silica fibers depends on the quality of the surface, the effect of rod surface cleaning procedure on the fiber strength has been investigated. Fused silica rods have been cleaned before fiber pulling using either Ethyl Alcohol (grey bars in figure 1) or an acid solution (white bars in figure 1) made by sulfuric acid, hydrogen peroxide and potassium bichromate. There is no difference between the cleaned and uncleaned rods (black bars in figure 1). An average value of $B = 4.05 \pm 0.55$ GPa can be extracted from figure 1. This must be compared with the breaking strength of C85 wires: $B_{C85} = 2.90 \pm 0.02$ GPa. The fused silica breaking strength is higher than the C85 value, but shows a larger fluctuation. This is mainly due to the fact that the fused silica breaking strength is dominated by surface defects.

The fused silica loss angle is shown in figure 2 versus the mode frequency. It is clear that the fused silica loss angle is two order of magnitudes lower than the C85 loss angle. The different frequency behavior is due to the different thermoelastic contribution. In figure 2, there are two different curves for fused silica fibers shown. The curve with solid triangles is taken by hanging a fiber with an intermediate massive bob to reduce the suspension recoil losses [7]. Since a small difference is measured between the fused silica with and without isulating bob, a low recoil loss contribution is expected in our apparatus.

The measurements of the silicate bonding strength are reported in figure 3, where the stress in MPa, is obtained dividing the force applied by the bonding surface. Firstly, it should be noted that, in order to avoid impurities in the bonding surfaces that can be, under stress, the starting point of a fracture, it is necessary to maintain a high cleanliness

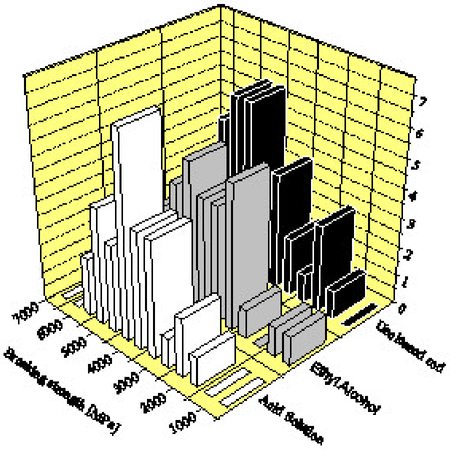

Figure 1. Breaking strength of fused silica fibers. White bars: acid solution cleaning procedure. Grey bars: Ethilic alchool cleaning procedure. Black bars: uncleaned fused silica rods

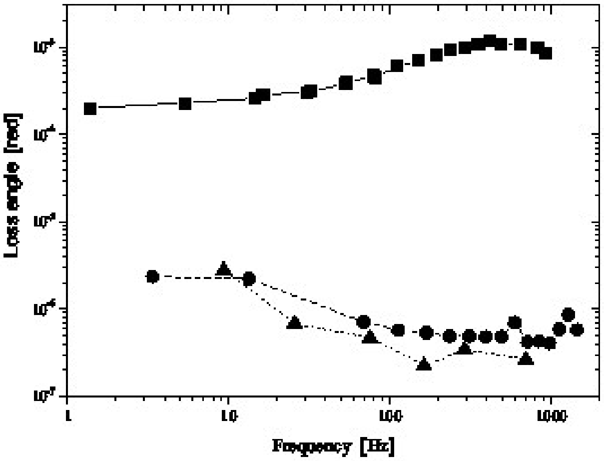

Figure 2. Loss Angle. Squares: C85 wire. Circles: Synthetic fused silica. Triangles: Synthetic fused silica with isolation bob

level during the entire bonding process. For this reason very pure KOH solution has been used and the bonding surfaces have been well cleaned with the acid solution, isopropanol alcohol and pure water. All the bonding processes has been performed under a class 100 laminar flux bench. Several strength test have been performed on cylindric samples with different flatness levels. Samples with flatness equal to λ/k - with $k = 10, 7, 4$ and

$\lambda = 633$ nm - have been silicate bonded. In figure 3, the samples with $\lambda/10$ flatness, tested after 44 days, show too low breaking stress. Under microscope analysis, they showed a poor bonding quality, possibly due to bad cleaning or low solution purity.

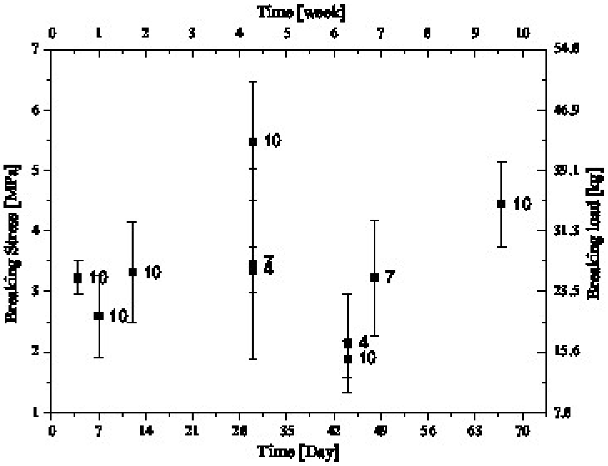

Figure 3. Silicate bonding strength: the numbers $k = 10, 7, 4$ close the the symbols indicate the flatness quality of the surface in terms of λ/k

4. Conclusions

Fused silica is a promising material for the suspension wires of the optics of a gravitational wave detector like Virgo. From the lower curve in figure 2, it is possible to extract the structural loss angle of the fused silica $\phi_w \simeq 3 \div 4 \times 10^{-7}$, which is more than two orders of magnitude lower than the loss angle of the C85 steel. The breaking strength of fused silica fibers is also larger than the corresponding value for C85 steel wires, currently adopted as reference solution. The large spread of the the breaking strength measures determines a decrease of the safety factor C_s for fused silica. Using fused silica fibres of $300\mu m$ of diameter to hang the Virgo mirror, a safety factor of $C_s \simeq 15\%$ is obtained; this value must be compared with the 65% adopted for C85 steel wires.

The use of potassium silicate bonded *ears* to attach the suspension wires to the mirror is compatible with the strength of this kind of bonding. The shape of the *ears* to be used in Virgo is still to be defined, but to have a safety factor about 3, in terms of breaking stress, a contact area larger than $150mm^2$, is foreseen. The effect of the silicate bonding on the pendulum Q for a Virgo like configuration must still be investigated, but previous measurements [8] on a smaller mirror showed promising results. Previous results by other authors [10] and preliminary measurements on the effect of the silicate bonded *ears* on the mirror Q in the configuration reported in [9] show that the substrate quality factor is not affected by the presence of the *ears*

If a full fused silica suspension will be realized in Virgo, a great improvement in the sensistivity is expected.

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