Mechanical quality factor of mirror substrates for Virgo

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Abstract. Thermal noise in the mirror substrates is expected to be the main limit to the Virgo sensitivity in the $50 \div 500$ Hz frequenzy range. The mechanical quality of the mirror substrates and the geometry of their suspension are shown to affect the noise level of the detector output. High mechanical Q have been obtained for different large fused silica substrates under Virgo suspension conditions. Moreover, calcium fluoride substrates are shown to provide a more promising option for the design of future cryogenic, low thermal noise interferometers.

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1. Introduction

In all the interferometric Gravitational Wave (GW) detectors the optical cavities are realized by suspending massive fused silica mirrors, where thermal fluctuations are an important source of noise. In Virgo thermal noise from the suspended optics is expected [1] to dominate the antenna sensitivity in the $50 \div 500$Hz range. The power spectrum of the surface displacement of the mirror parallel to its axis is given by the fluctuation-dissipation theorem. Currently, two approaches are mostly used to evaluate the thermal noise level in a continuous extended medium: modal analysis [2] or direct application of the fluctuation-dissipation theorem [3, 4, 5, 6]. In both the methods it is important to determine the value of the loss angle of the resonant modes to extrapolate the corresponding thermal noise power spectrum [7]. As a matter of fact, the loss angle $\phi(\omega)$, as determined through direct measurement of the mechanical Q of the suspended mirror, is the combination of two contributions: the internal substrate loss angle and the undesired loss angle due to the substrate-suspension coupling. Of course, such an additional term depends on the geometry of the mirror suspension and on the spectrum of the substrate excitations. By means of the interferometric technique outlined in Sec. 2, we have measured the quality factor of large mirror substrates in suspension configurations as close as possible to the Virgo final design [8].

2. Experimental apparatus

A Virgo mirror consists of a 21.2kg 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 70cm. The wires are made of C85 harmonic steel and their diameter is 0.2mm [9]. Four fused silica prisms are inserted as spacers between the mirror lateral surface and the suspension wires. The apparatus is kept under vacuum (of about 10^{-4} Pa) placed on an optical table for seismic isolation.

The mirror modes are excited electrostatically by means of one or more comb capacitors placed close to the test mass surface and driven by high-voltage signals (sinusoids or band-limited white noises). The surface vibration is read through a Michelson interferometer, where one arm is formed by the beam splitter and the test mass itself, and the other by the beam splitter, an intermediated small mirror and a small fused silica disk acting as end mirror. Note that, as both the test mass and the small fused silica disk are uncoated, our optical device operates by virtue of the fused silica reflectivity, alone. The interferometer output port is read by a photodiode placed outside the vacuum chamber. The interferometer is locked on the grey fringe (half-maximum output power) by modulating the length of the second arm through the small intermediate mirror driven by a piezoelectric actuator. The low-frequency pendulum oscillations are read from the output photodiode, filtered and fed back to the piezo. The modal frequencies f_i and the quality factors Q_i are determined by measuring the ring-down decay time of the relevant excited mode.

3. Experimental data

We tested substrates made in Suprasil and in Herasil (see Table 1). Although in our work the mirror suspension geometry was chosen the closest to the Virgo final design, several alternate configurations have been tested, as well, for the sake of a comparison. The substrate *Sub2* was produced by Heraeus with both faces well polished ($\sim \lambda/10$), but

Table 1. Geometric characteristics of the substrates

ID	Substrate material	Diameter (mm)	Thickness (mm)	Lateral surface
Sub1	Heraeus Herasil	350	100	rough
Sub2	Heraeus Suprasil 3	350	100	rough
Sub2a	Heraeus Suprasil 3	350	100	polished
Sub3	CaF_2	180	38	rough

rough lateral surface. The relevant Q factors have been determined with and without side spacers. Then, the lateral surface of the mirror has been polished (just up to a see-through level) and two flat strips have been machined and polished to $\lambda/10$ level in view of future clamping tests (*Sub2a*). A comparison between the Q values thus measured under different condition is shown in Fig. 1. As in Virgo the mirror position is controlled

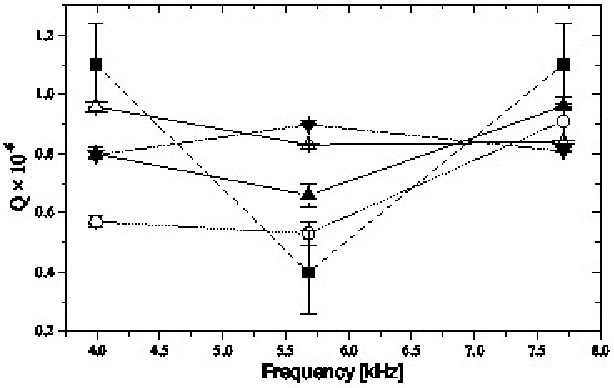

Figure 1. Q factors of the Suprasil 3 substrates *Sub2* and *Sub2a*; solid squares: *Sub2* without spacers; open circles: *Sub2* with spacers and suspension wire loops set at a distance d = 5cm; solid up-triangles: *Sub2a* with spacers and d = 5cm; open up-triangles: *Sub2a* with spacers and $d = 2.5$cm; solid down-triangles: *Sub2a* with spacers and $d = 0.2$cm.

by a magnetic actuator, the effect of glueing four samarium-cobalt magnets (4mm across and 3mm long) on the substrate surface (close to the edge) has been quantified, too 2. The glue is a high vacuum compatible ceramic glue produced by Aremco (Ceramabond). A material of potential interest for the optics of the GW interferometers of the next generation is calcium floride (CaF_2), widely used in optical components and recently made available in large samples. For this reason we measured for the first time the Q of a relatively large cylinder of CaF_2. The lateral surface of this substrate was rough and the machining irregular. The results are shown in Fig. 3.

4. Discussion and conclusions

It is well known that Q measurements on any mechanical resonator are affected by excess losses due to a variety of mechanisms, sometimes regarded as spurious. In most cases experimentalists try to reduce excess losses by adjusting the geometry of the resonator and its support or selecting the best performing materials for its suspensions. In our case, we are interested in the performances of our system under the Virgo standard configuration.

The data displayed in Fig. 1 for the Suprasil 3 substrate show that the Q of the three lowest modes are differently affected by the geometry of the suspension and

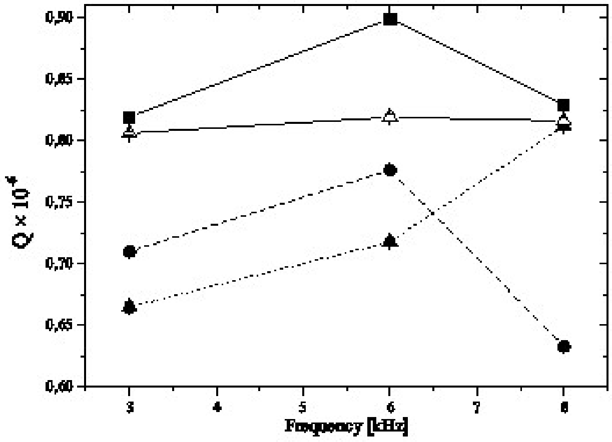

Figure 2. Q factors of the Herasil substrate; solid squares: *Sub1* substrate without any magnet on the flat surfaces; solid circles: *Sub1* substrate with four magnets on one flat surface; solid triangles: *Sub1* substrate with four dummy magnets (in brass) on one flat surface; open triangles: *Sub1* substrate with four dummy magnets (in fused silica) on one flat surface attached via silicate bonding.

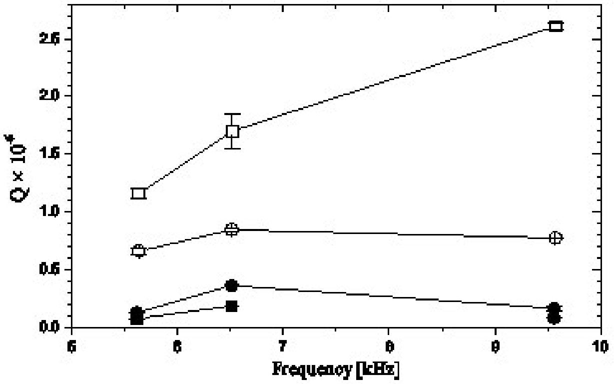

Figure 3. Q factors of the calcium fluoride substrate *Sub3* with (solid symbols) and without side spacers (open symbols); circles: magnets glued to the substrate (coil-magnet excitation); squares: without magnets (electrostatic excitation). The solid square corresponding to the third mode is missing because its frequency exceedes the limits of our experimental apparatus. The third mode in the configuration represented by the solid circles undergoes frequency splitting, hence the two close dots.

the surface quality of the substrate. The characteristics of the first three modes are reported in Table 2 (notation is as in [13]), where n represents the number of nodal diameters [14], the parity ξ is one for the odd modes (the mirror faces vibrate in phase) and zero for the even modes (the mirror faces vibrate opposite in phase) and the index m is the order number for a given value of n and ξ. The modal frequencies measured for the two substrates *Sub1* and *Sub2* are compared in Table 2 with the relevant frequencies computed by means of the numerical code *Cypres* [13]. The different sensitivity (although with a small Q decrement overall) of the first three modes to the spacer insertion may be due, as suggested by other authors [10, 11], to the different modal geometry of the mirror deformations. In Virgo the side spacers are required in order to ensure a high Q for the pendulum mode of the mirror suspension [8]. The 5cm distance between the two suspension loops is dictated by the final choice for the *pitch* mode frequency of the suspended mirror. In any case, we investigated how changing such distance affects the Q of the mirror. From Fig. 1 it is evident that the overall effect is small, but the vibration modes are differently affected. Probably this is due to the coupling between the mirror and the suspension wires because each mode shows a different vibration shape. The lateral surface polishing effect is also illustrated in Fig. 1.

Table 2. Characteristics of the three lowest vibration modes

n	ξ	m	Frequency (Hz)		
			Cypres	*Sub1*	*Sub2*
2	1	1	3984	3993	3991
0	1	1	5704	5690	5678
2	0	1	7682	7713	7709

As shown in Fig. 2, glueing four magnets on the substrate *Sub1* causes an overall decrement of the mirror quality factor. To evaluate the possible contribution to the energy loss due to the eddy currents [12] generated by the magnets on the vacuum chamber walls, we measured the Herasil substrate Q with four dummy (brass) magnets glued (Fig. 2, solid up-triangles). All the measured Q values are comparable and the differences are essentially due to the dissipation caused by the glue losses. To minimize this effect, we tested a chemical bonding procedure named *silicate bonding*: four small fused silica cylinders (7.75mm diameter and 3mm height) have been attached on the mirror flat surface by potassium-silicate bonding. In Fig. 2, the Q values of all the three modes under these conditions are clearly higher than those from our previous tests with real magnets and brass dummies. With silicate bonded cylinders, mode (201) and (211) quality factors come very close to the relevant values obtained in the absence of any magnets. Thus, to reduce the residual dissipation effects showed by mode (011) of the Virgo mirrors, smaller fused silica cylinders could be used to connect the magnets to the substrate.

Figure 3 displays our Q data for the CaF_2 substrate. It is apparent that the fused silica spacers damp dramatically the Q factor of the mirror. This effect could be traced back to the different mechanical properties of CaF_2 or simply to the smaller size and mass of the sample we tested. Note that the four magnets reduce further the Q of this substrate. The Q factor for the CaF_2 substrate is considerably higher than for the fused silica samples. From a mechanical point of view, CaF_2 is a more promising material for the optics of future GW interferometers also because it allows, at least in principle, the design of cryogenic suspensions; indeed, at variance with SiO_2, no low temperature loss-angle peak was ever observed in CaF_2 samples.

Since the quality factors of the tested Herasil and Suprasil samples are quite similar and, according to the Virgo final design, the lateral surfaces of the mirrors will be well polished, substrate *Sub2* can be taken as an appropriate reference solution for the computation of the mirror thermal noise contribution to the Virgo sensitivity curve (Fig. 4). From Fig. 1 the average Q value of *Sub2* is $Q \simeq 0.8 \times 10^6$, namely very close to the Virgo specifications.

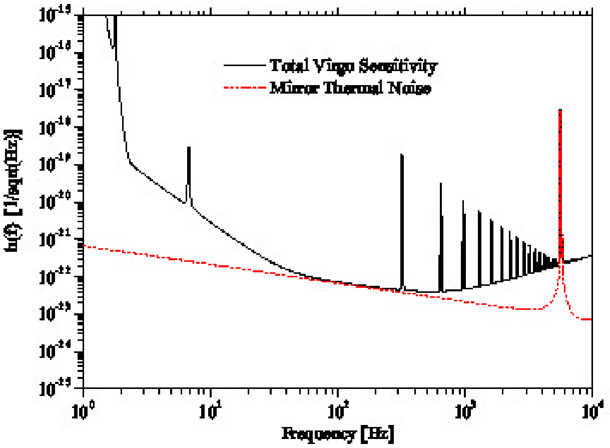

Figure 4. The Virgo sensitivity curve [1] (solid line) and the expected mirror thermal noise contribution (dashed line).

References

[1] M. Punturo, *The VIRGO sensitivity curve*, VIR-NOT-PER-1390-51, Virgo Internal Note (2001) and see *http://www.virgo.infn.it/senscurve/*

[2] F. Bondu, J.Y.Vinet, Phys. Lett. **A198** (1995) 74

[3] J.Y. Vinet, VIR-LAS 10/2000, Virgo Internal Note (2000)

[4] Yu. Levin, Phys. Rev. **D57** (1998) 659

[5] F. Bondu, P. Hello, J.Y. Vinet, Phys. Lett. **A246** (1998) 227

[6] Y.T. Liu and K.S. Thorne, Phys. Rev. **D62** (2000) 122002

[7] P. Amico et al., *Submitted to Rev. Sci. Instr.* (2001)

[8] G. Cagnoli et al., Rev. Scien. Instr. **71** (2000) 2206

[9] G. Cagnoli et al. Phys. Lett. **A255** (1999) 230

[10] W.J. Startin, M.A. Beilby, P.R. Saulson, Rev. Sci. Instr. **69** (1998) 3681

[11] K. Numata et al., Phys. Lett. **A284** (2001) 162

[12] G. Cagnoli et al., Rev. Sci. Instr. **69** (1998) 2777

[13] F. Bondu, PhD Thesis: *Étude du bruit thermique et stabilisation en fréquence du laser du détecteur interférométrique d'ondes gravitationelle Virgo*, 10/1/1996 (unpublished)

[14] G.W. McMahon, Journ. of the Acoustical Soc. of America **36(1)** (1964) 85