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General Physics

**Energy dissipation in the pendulum mode of the test mass suspension
of the gravitational wave antennae.**

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Abstract:

The results of measurements of the relaxation time of all fused silica massive pendulum are presented. The relaxation time obtained was ≈ 3 years, which corresponds to the quality factor $Q \approx 1 \times 10^8$.

One of the key factors which limit the sensitivity of the gravitational wave antennae is the thermal motion of the test mass (see, e.g., [1,2]). The only possibility that follows from the fluctuation-dissipation theorem, which allows to reduce this noise, is to increase the quality factors Q of all modes in the test mass (in the mirror) and in its suspension, in other words, to reduce the energy dissipation in all modes. The pendulum and the violin modes in the suspension of the mirrors are the most important. In our preliminary tests [3,4] we have demonstrated that the quality factors of these modes in all fused silica suspension are between $Q=(0.5-1) \times 10^8$. These values are several orders higher than the values obtained when the mass was suspended by steel music wires [5]. On the other hand the obtained high values of Q can not be directly extrapolated for the full scale value of the mirror mass $m \approx 10 \text{ kg}$ because these Q 's were obtained in a relatively modest model of the mass $\approx 30 \text{ g}$. Thus the logical step after the experiments [3,4] was to test the Q with substantially heavier mass. The first tests of the violin mode Q 's with the mass $m \approx 1.6 \text{ kg}$ demonstrated that Q_{viol} are approximately the same [6]. In this article we present the results of the experiments in which the Q factor of pendulum mode of all fused silica oscillator (with total mass 2 kg) was measured.

In the tested model (see Fig.1) a cylinder of fused silica with diameter $D=10 \text{ cm}$ and length $L=12 \text{ cm}$ was suspended by two fibers of very pure silica (the level of impurities $< 3 \times 10^{-5} \%$) which had the length $l=20 \text{ cm}$ and the diameter $(1.5-2) \times 10^{-2} \text{ cm}$. The total mass of the cylinder $M \approx 2 \text{ kg}$. The fibers were welded

to the bumps (about 0.5 cm high each) which were carved in the cylinder and in a massive upper silica slab. The slab was rigidly attached to the upper part of the cage in which the pendulum was situated.

The key obstacle in obtaining the value $Q \approx 10^8$ and higher ones was the leakage of the mechanical energy into the support (the recoil losses). To reduce this effect it was necessary to have a very small ratio of the rigidity of the chosen mode of the oscillation to the rigidity of the lowest mode of the support. This condition led us to the use of a rigid cage made of aluminium alloy (the eigen frequency of its lowest torsional mode being $\omega_{sup} \approx 4 \times 10^3$ rad/sec) as a support and the use of the torsional-pendulum mode of the cylinder oscillation which had $\omega_{tors-pend} \approx 2$ rad/sec for the distance $2a \approx 2.5$ cm. Relatively simple calculations which we omit here permitted to estimate the limit of $Q_{tors-pend}$ at the level 10^9 due to the recoil losses for above values of the $\omega_{tors-pend}$ and ω_{sup} and with the mass of the cage $m_{cage} = 25$ kg.

All accumulated experience [3,4,6] about the losses in the fused silica fiber permits one to assume that a substantial part of the material losses may be described by the model of structural dissipation[7]. According to this model the Young's modulus Y and the shear modulus G of the material have the imaginary parts which are independent of the frequency:

$$Y = Y_0(1 + i\phi_Y), \quad G = G_0(1 + i\phi_G),$$

where ϕ_Y and ϕ_G are the angles of losses in the material. These two values define the value $Q_{tors-pend}$:

$$Q_{tors-pend}^{-1} \approx \frac{\pi \cdot Gr^4}{Mga^2} \phi_G + \frac{1}{2l} \cdot \sqrt{\frac{\pi \cdot Yr^4}{2Mg}} \phi_Y$$

where g - is the gravitational acceleration, r - is a radius of the fibers. Substituting in this formula $\phi_Y = \phi_G = 1,4 \times 10^{-7}$ (see [5]), $a = 1.25 \text{ cm}$, $r = 1 \times 10^{-2} \text{ cm}$, we can expect $Q_{tors-pend}^{-1} \approx 10^{-9}$ to be reached.

In the described experiments four pendulum suspensions were tested, and the values obtained were $Q_{tors-pend} \approx (0.5 - 1) \times 10^8$. These values are more than one order smaller than the expected $Q \approx 10^9$. Additional losses could be explained due to several small particles of dust on the fiber's surface and due to the sedimentation of silica vapour on the surface of the fiber near the welding area.

Fig. 2 presents the measured time dependence of the amplitude of torsional-pendulum mode free oscillations in one of our tests. The recorded relative decrease of the amplitude 2×10^{-3} during two days corresponds to the relaxation time $\tau_m^* = 4.8 \times 10^7 \text{ s}$ ($\pm 10\%$). The gas pressure in the vacuum chamber was $2 \times 10^{-6} \text{ Torr}$. Introducing the correction to this pressure we obtain the divine value $\tau_m^* \approx 1 \times 10^8 \text{ s} \approx 3 \text{ years}$, which corresponds to $Q_{tors-pend} \approx 1 \times 10^8$ ($\pm 25\%$).

Concluding this brief report it is worth-wile emphasizing that the obtained values of $Q_{tors-pend}$ as well as Q_{violin} [6] allow to reach the sensitivity of the laser interferometer gravitational wave antennae at the level of the Standard Quantum

Limit when the random fluctuations of the center of mass of the mirror is defined mainly by the back action of the quantum meter. We guess that a further improvement of the technology of the described suspension of the test masses may permit higher values of the quality factors predicted in [2] to be obtained.

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Figure captions

Figure 1. Design of the pendulum and the suspension support structure.

Figure 2. Time dependence of amplitude of torsional-pendulum mode oscillation during a free decay.

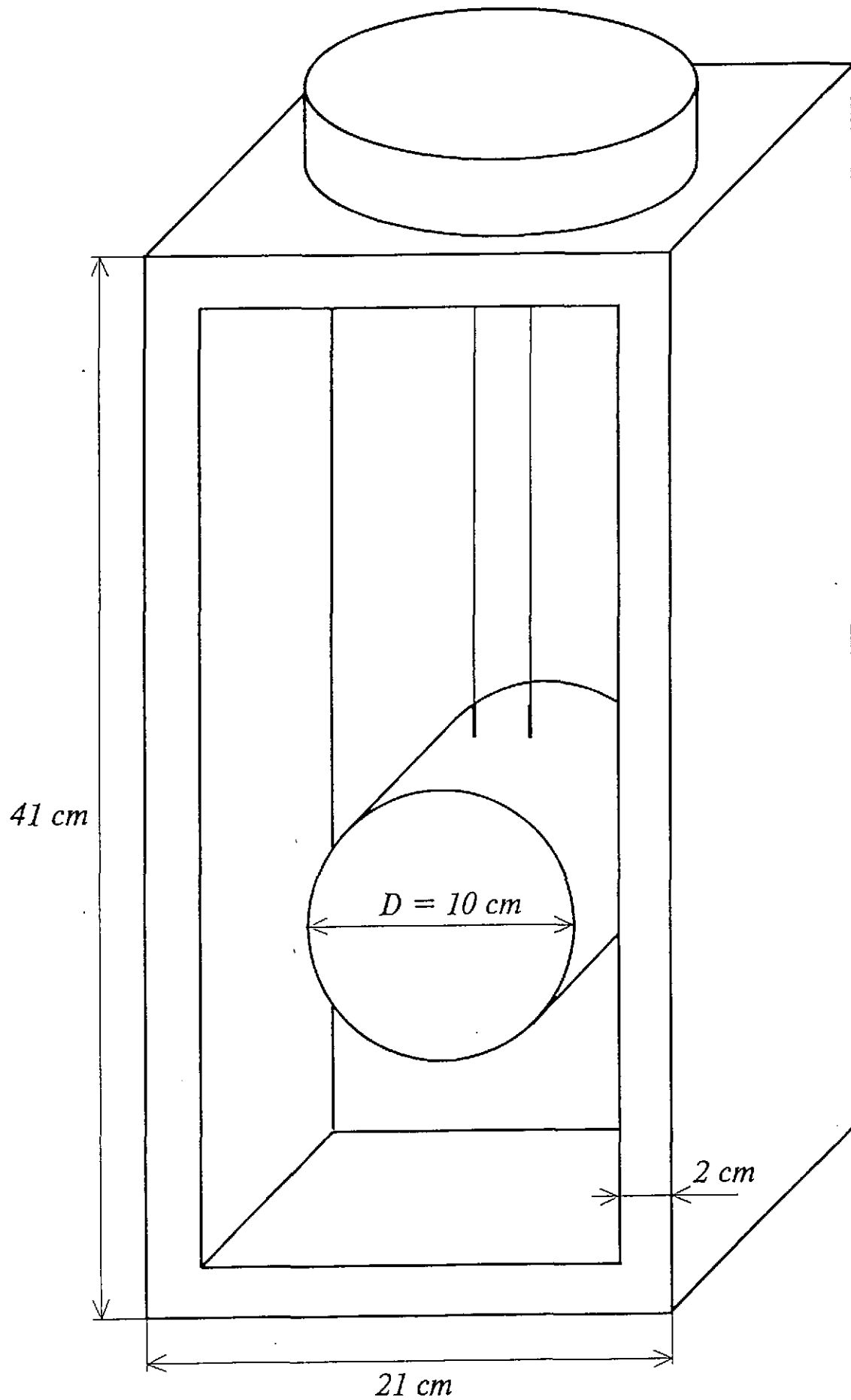


Figure 1

