TEST MASS DAMPING ASSOCIATED WITH ELECTROSTATIC ACTUATOR

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Abstract. The main sources of damping of the test mass oscillation associated with electric field of a multistrip actuator are described. The possibility of the cool electrical damping with the small increase of the test mass thermal noise is discussed.

In the advanced projects of laser interferometric gravitational wave detectors (LIGO-II and others) the goal is to approach to the Standard Quantum Limit of sensitivity[1]. To reduce the suspension thermal noise the fused silica suspension of the mirrors is planned to be used where the Q-factors of the pendulum and violin modes exceed 10^8. The actuators needed to provide fine control of the mirror position also must not create the additional fluctuating force acting on the mirror in the detector frequency band. This fluctuating force is generated due to the damping of the mirror oscillation caused by the actuator. We present results of our research of the pendulum damping associated with the electrostatic actuator.

The multistrip electrostatic actuator that does not use a conductive coating on the mirror is the most promising one. It consists of series of plain strip electrodes alternatively at positive and negative potentials which are placed near the mirror surface. The detailed analysis of forces produced by the multistrip electrostatic actuator was given in [2]. We studied the excess damping of the bifilar all-fused silica torsion pendulum resulted from the electric field of the actuator (see Fig.1). The pendulum bob was a 0.5 kg fused silica cylinder with two fused silica cones attached by means of hydroxide-catalysis bonding technique. This cylinder was manufactured and provided to us by S. Rowan and J. Hough from the University of Glasgow. It was suspended on two fused silica fibers 25 cm in length and 200 μm in diameter. The fibers were fabricated and brought from Caltech by P. Willems. This pendulum had the Q-factor of about 10^8 .

The fused silica plate with the actuator was mounted parallel to the end face of the suspended cylinder with the gap of 2-3 mm. Two sets of strips were sputter-deposited on the surface of this plate. Each strip had the width of 4 mm and was separated from the next one by the 3 mm gap. One set of strips was grounded. The

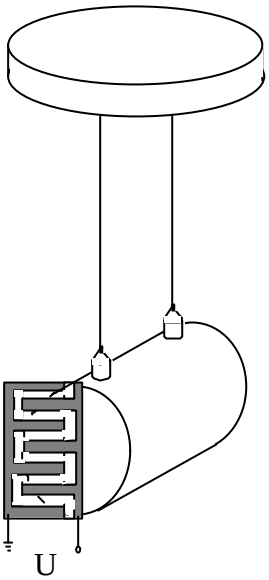

Fig1. Schematic of the pendulum with electrostatic actuator.

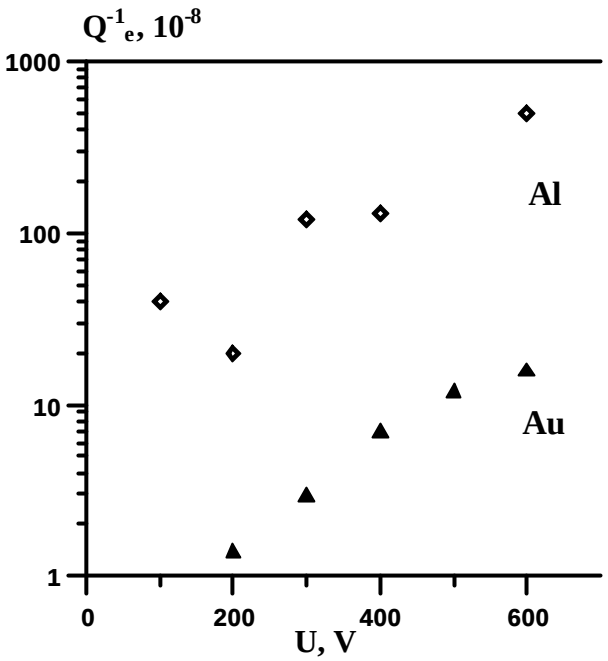

Fig.2. Electric field damping associated with different material of electrodes.

voltage up to 1500 V was applied to the other set. The actuator exerted force up to 10^{-4} N. The center of the actuator plate was displaced from the center of the cylinder by 1.5 cm to excite the torsion motion of the pendulum.

We have found two main mechanisms of the pendulum damping Q_e^{-1} resulted from electric field of the actuator. The first one is associated with the surface of metal electrodes of the actuator. The dependence of damping on the applied voltage V for aluminum and gold film electrodes (in this case one electrode from the each pair was placed on the pendulum another was on the plate of the actuator) is shown in Fig. 2. The aluminum electrodes were baked *in situ* at about 200°C in order to obtain reproducible results. Such baking reduced Q_e^{-1} as well. This effect was probably caused by the removal of adsorbed water from the surface of electrodes. A difference in the magnitude of damping can be explained by the presence of oxide layers on the surface of aluminum electrode. Electron transitions between local surface states in the oxide layers or their polarization under the action of the electric field may be responsible for the excess damping. Therefore we used the gold film electrodes which provide the minimal damping.

The experiments have shown that the damping Q_e^{-1} of the pendulum associated with the electric field of the multistrip electrostatic actuator strongly depended on properties of the suspended fused silica cylinder end surface [3].

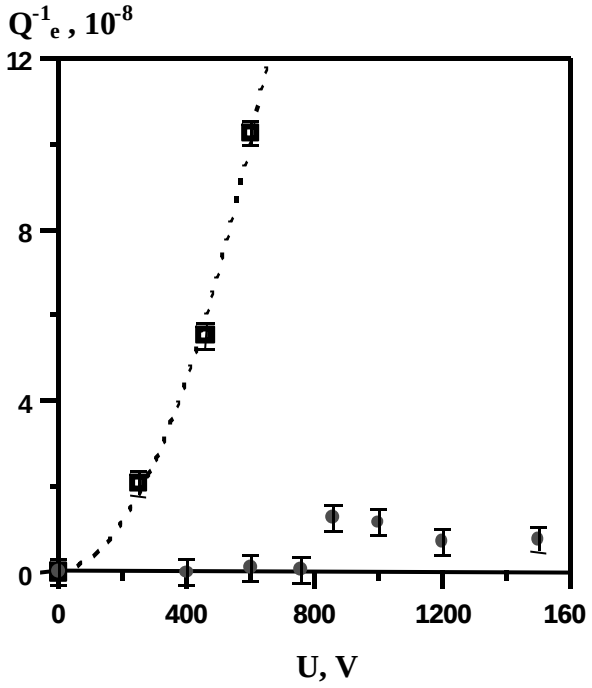

Fig.3. Electric field damping before (ð) and after (•) thermal treatment of the fused silica cylinder surface.

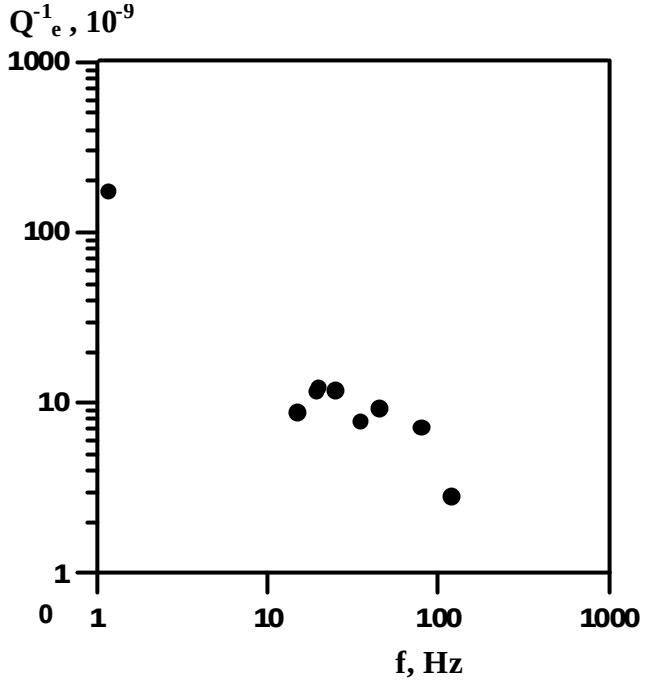

Fig.4. Variation of damping as a function of electric field frequency.

Fig.3 shows the measured damping Q_e^{-1} as a function of the dc voltage applied to the actuator. Curve ( ) was obtained for the mechanically polished end face of the fused silica cylinder cleaned in acetone and ethanol. This curve is well fitted by U^2 dependence. Afterwards the thermal treatment of the fused silica cylinder end face by the flame of an oxygen/natural gas torch was carried out. This treatment was done by applying the flame directly to the surface of the cylinder and moving the flame back and forth across the surface. The duration of the flame treatment was about 10 min. Immediately afterwards the vacuum chamber with the pendulum in it was evacuated. Curve (•) shows Q_e^{-1} measured after such a treatment that was repeated twice. This reduction of the damping remained after opening the chamber and keeping the pendulum in the ambient atmosphere during some hours. We could not yet explain this phenomenon. Mechanical polishing of a fused silica sample results in the formation of the surface layer consisting of products of hydrolysis of SiO_2 and having the porous structure that can adsorb water [4]. The flame treatment is likely to remove this layer. It is interesting to compare our results with those presented in [5]. The authors have found flame polishing had reduced surface mechanical losses in a fused silica sample and had allowed them to reach the lowest measured at the room temperature value of the intrinsic loss in fused silica.

The important feature of the damping associated with the electric field of the actuator is that it decreases if the ac electric voltage is applied instead of the dc voltage. The damping roughly followed a $1/f$ law, where f was the frequency of the electric field. A plot of the damping associated with the electric field Q_e^{-1} as a function of the frequency of the applied ac voltage of 500 V is shown in Fig. 4. This means that for the suspended test mass the frictional coefficient associated with the electric field of the actuator decreases approximately in inverse proportion to the operating frequency of the detector.

There is one more mechanism of the damping associated with the electrostatic actuator. It is the damping due to Joule loss in the electrical circuit of the actuator. The motion of the suspended body results in a change of the capacitance between the electrodes and a current flowing through the resistor R in the circuit, dissipating the energy of the pendulum. Usually, decrease of resistance R reduces this damping. In our experiments R was about of 1 kOhm and the damping resulted from this mechanism was negligible.

We would like to attract attention to the possibility to introduce by this way the additional damping in a mechanical oscillator which produces a small fluctuating force if the resistor R is cooled. This is called the partial cooling method (see for example [6]). For example, it may be used in order to reduce Q of the violin modes in the fused silica suspension because too high Q of the certain violin modes can impede the fine control of the interferometer [7]. In this case the electrode with the applied constant voltage U is placed near the oscillating surface with a separating gap d and capacitance C. The following additional electrical damping is created (a parasitic capacitance is not taken into account):

$$Q_R^{-1} = \frac{U^2 C}{m w_0^2 d^2} \frac{w_0 RC}{1 + w_0^2 R^2 C^2},$$

where m and w_0 are the mass and natural frequency of the mechanical oscillator.

The power spectral density of the fluctuating force, according to the Nyquist theorem is given by

$$S_F(w) = 4K_B m w_0 (T_m Q_m^{-1} + T_R Q_R^{-1}),$$

where T_m and T_R are temperatures of the oscillator and the resistor, Q_m^{-1} is the nonelectrical damping of the oscillator. If $T_R << T_m$ (for example, the resistor is placed into the helium refrigerator) the increase in the total thermal noise is inconsiderably less than the increase in the damping. It is important that the described above damping associated with the surface of electrodes can be done negligible.

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