Relaxation effects in the fused silica test mass interacting with the ESD.

D.V. Koptsov, L.G. Prokhorov, V.P. Mitrofanov
Faculty of Physics, Moscow State University, Russia
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LIGO Scientific Collaboration

Introduction

A potential source of the test mass noise is associated with the interaction of polarized fused silica test mass with electric field of the electrostatic drive (ESD). Previous measurements [1,2] have shown that the ESD redistributes charges on the test mass mirroring the electrode pattern and the accumulated charge increases over time. We have developed an experimental setup to investigate the interaction between ESD and fused silica test mass, and a numerical model describing this interaction.

Experimental Setup

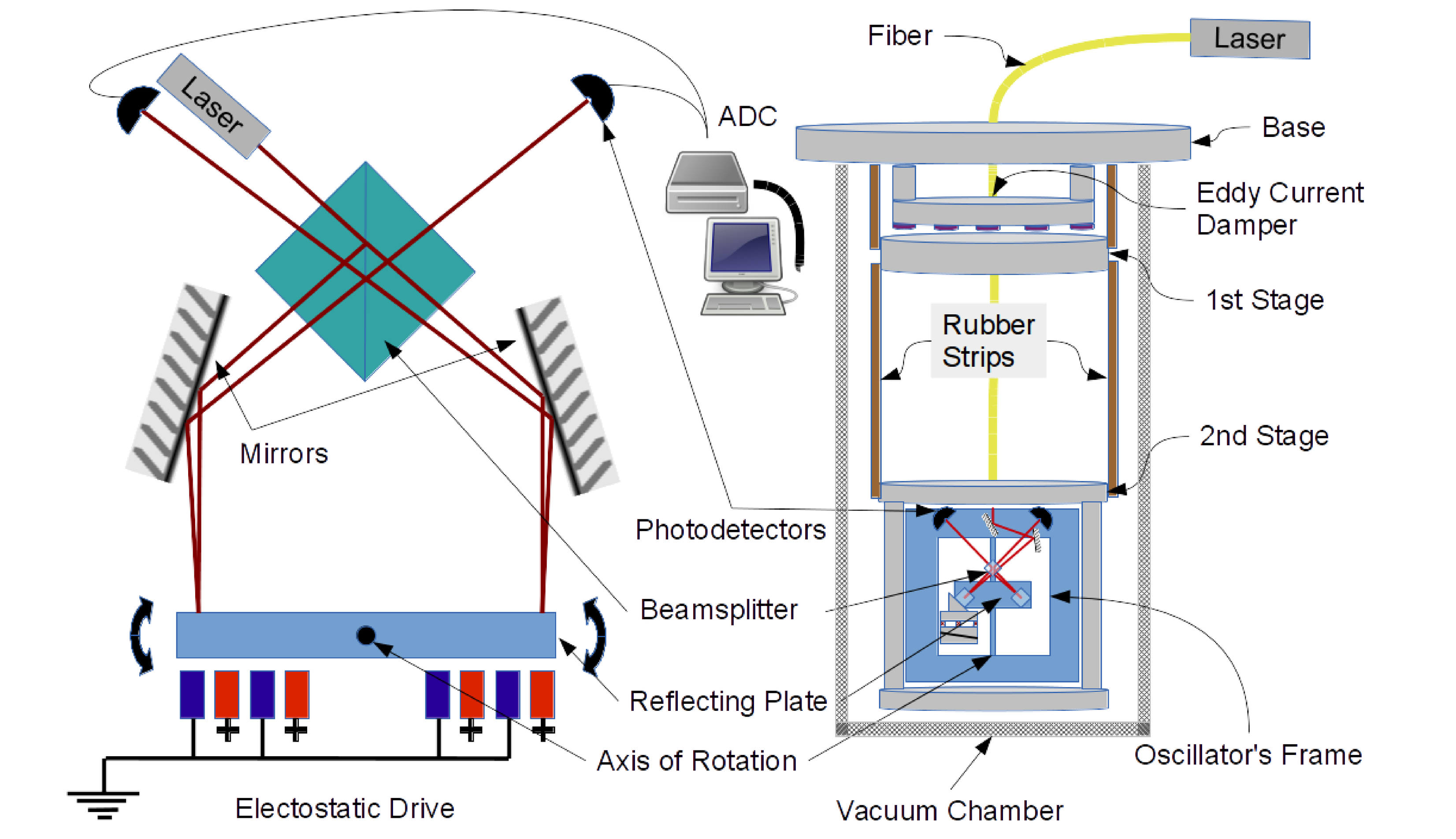

Figure 1 : Schematic of the experimental setup (left) and seismic isolation suspension system (right)

The experimental setup is an upgrade of our previous setup [3]. A fused silica plate ($25 \times 10 \times 2\, mm^3$, $m \approx 1.1g$) welded via fused silica fibers to a rectangular frame forms a torsional oscillator. Two plates with comb electrodes (the ESD) are placed near the oscillating fused silica plate. The separation gap is about $1mm$, electrode strips are $1mm$ wide and are separated by $1mm$. Each plate with electrodes has independent voltage source so that we can apply DC, AC or DC+AC voltage to them. The torsional oscillator's resonant frequency is $f_0 = 63.13Hz$, the quality factor $Q_0 \approx 10^6$ in vacuum and $Q_{air} \approx 2100$ in air. The deflection angle is measured by a specially designed Michelson interferometer [3] (Fig. 1). In order to provide seismic isolation oscillator's frame and Michelson interferometer are suspended as a double pendulum with upper stage damped by an eddy current damper.
Considering a simple model, the moment of force acting on the oscillator's plate from one of the ESD electrodes group may be written as

$$M(t) = A\left[U_{=}(t) + U_{\sim}(t)\right]^2 + B\left[U_{=}(t) + U_{\sim}(t)\right] q_{eff}(U_{=}, t) \qquad (1)$$

where $q_{eff}(U_{=}, t)$ is an effective charge, accumulated on the silica plate. We calculate the moment of force by applying AC voltage at $37Hz$ and measuring the forced oscillation's amplitude [3].

Numerical Model

A numerical model has been developed using Comsol Multiphysics©. The model is simulating charge accumulation and the corresponding time dependence of the interaction force between the ESD and fused silica test mass. In order to simplify calculations and decrease computing time, an axisymmetrical geometry has been used (Fig. 2). Fused silica surface is modelled as a thin layer ($d = 0.1mm$) on top of fused silica mass opposite the ESD. This layer contains all the charges, the rest of test mass contains no free charges. Voltage distribution has been computed with Poisson's equation and charge dynamics with Nernst-Planck equation:

$$\vec{E} = -\vec{\nabla} V$$

$$\vec{\nabla}\vec{D} = \rho \equiv \rho_i - \rho_e$$

$$\frac{\partial \rho_k}{\partial t} + \vec{\nabla}\left(-D_i \vec{\nabla}\rho_k - z_k \mu_k \rho_k \vec{\nabla} V\right) = 0$$

$$\vec{n}\left(-D_i \vec{\nabla}\rho_k - z_k \mu_k \rho_k \vec{\nabla} V\right)\Big|_{\Sigma} = 0$$

where $k = e, i$ - index of negative and positive charges, $\mu_{e,i}$ - mobility of negative and positive charges, $D_{e,i}$ - diffusion coefficient, $z_{e,i} = \pm 1$ - charge sign.

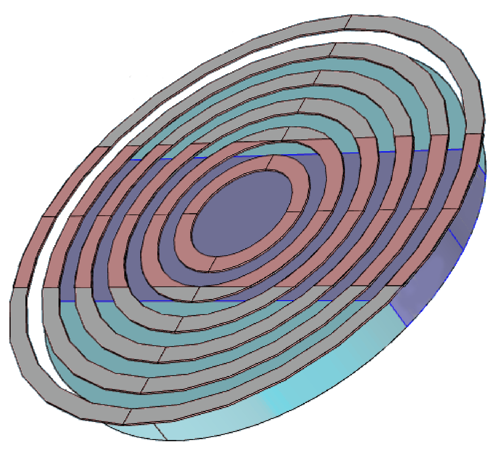

Figure 2 : Geometry model used in numerical simulation: selected purple block has the dimensions of the real oscillator's plate. Width and separation of ESD rings copy that of real ESD strips.

Relaxation of the Interaction Force

All measurements were carried out in air in order to accelerate relaxation processes. Dependence of the interaction force relaxation time on humidity agrees with the model suggested in [4] (Fig. 3).
Time evolution of the forced oscillations amplitude (scaled to the moment of force) is shown in Fig. 4, the corresponding simulation results are shown in Fig. 5. At first the ESD is turned off (black), then $U_{=} = 560V$ is applied to the ESD (red), then the ESD is turned off (blue).

Initial increase in the moment of force is due to the term $A \cdot U_{=} \cdot U_{\sim}$ in Eq. (1). Further increase in the moment of force reflects the accumulation of charge under the influence of the electrostatic field created by the ESD.
When the ESD is switched off, the accumulated charge relaxes. At humidity $h \approx 40\%$ the characteristic time of the accumulation is $\tau_{acc} \approx 2100s$ and of the relaxation is $\tau_{rel} \approx 1050s$. Taking into account different surface areas in experiment and simulation and AC voltage amplitude $U_{AC} = 2.5V$ used in the experiment, we can scale the force, computed in numerical model to the moment of force measured in the experiment.

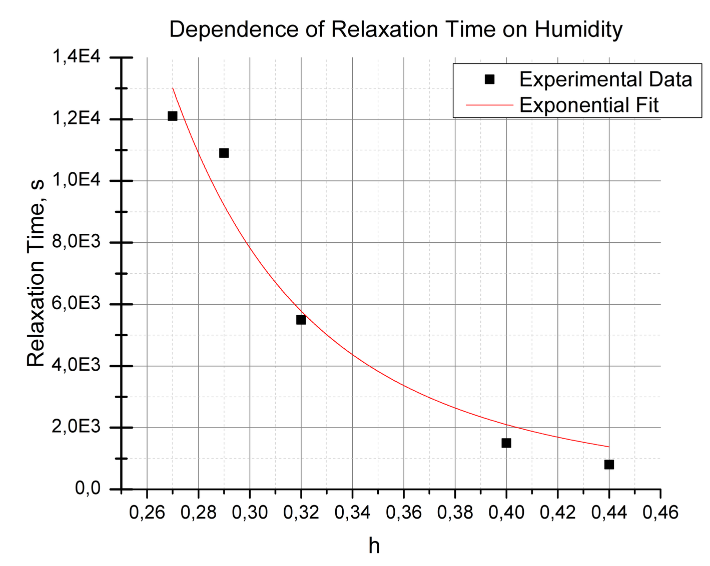

Figure 3 : Dependence of the interaction force relaxation time on humidity h fitted with exponential function $\tau(h) = \tau_0 \exp(b\sqrt{(1-h)/h})$

Numerical simulation with mobility $\mu_i = 5 \times 10^{-12} m^2/Vs$ and surface charge density $\rho_s = 10^{-6} C/m^2$ gives a good agreement with the measurements: accumulation and relaxation characteristic times, initial moment of force after the ESD has been switched on and the relative increase of the moment of force caused by the accumulation of charge agree by order of magnitude.The model is still under development and the work continues to resolve several issues, for example, charge accumulation is not «smooth» yet.

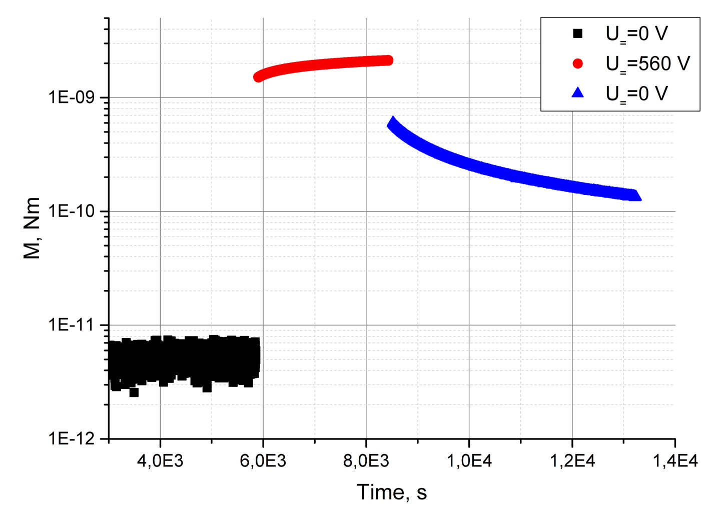

Figure 4 : Time evolution of the moment of force acting on the fused silica plate when a step DC voltage is applied to the ESD.

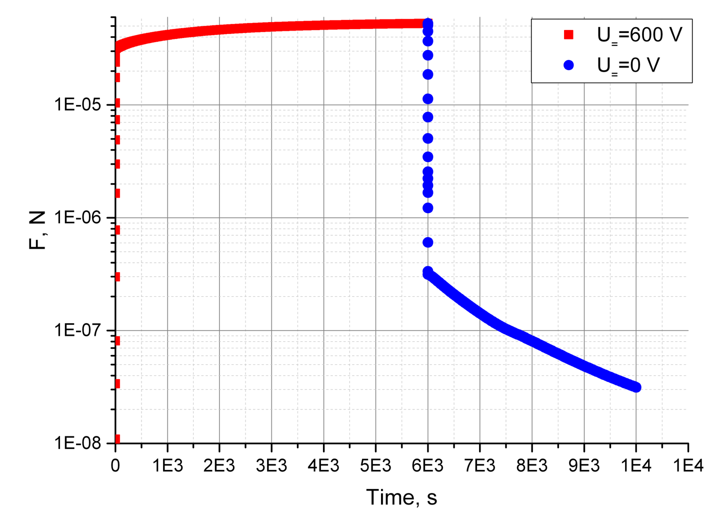

Figure 5 : Time evolution of the force acting on the fused silica plate when a step DC voltage is applied to the ESD. (Numerical simulation)

Noise Measurements

Power spectrum density of moment of fluctuating force has been measured when the ESD was grounded and when high voltage was applied to the ESD. Sensitivity close to the one limited by thermal noise of the oscillator has been reached near the resonant frequency. Additional noise has been observed when DC voltage $U_{=} = 860V$ was applied to the ESD (Fig. 6, blue curve). It roughly fits $1/f^2$ dependence (Fig. 6, green curve) and may be caused by the charge redistribution. Further investigation of this effect is in progress. Notice that the noise created by fluctuating electrostatic charges on fused silica surface has been measured at frequencies below $10^{-3}Hz$ by Glasgow group [5]. In our setup measurements have been carried out in the frequency range of Advanced LIGO, however in order to decrease significantly the charge relaxation time they have been performed in air.

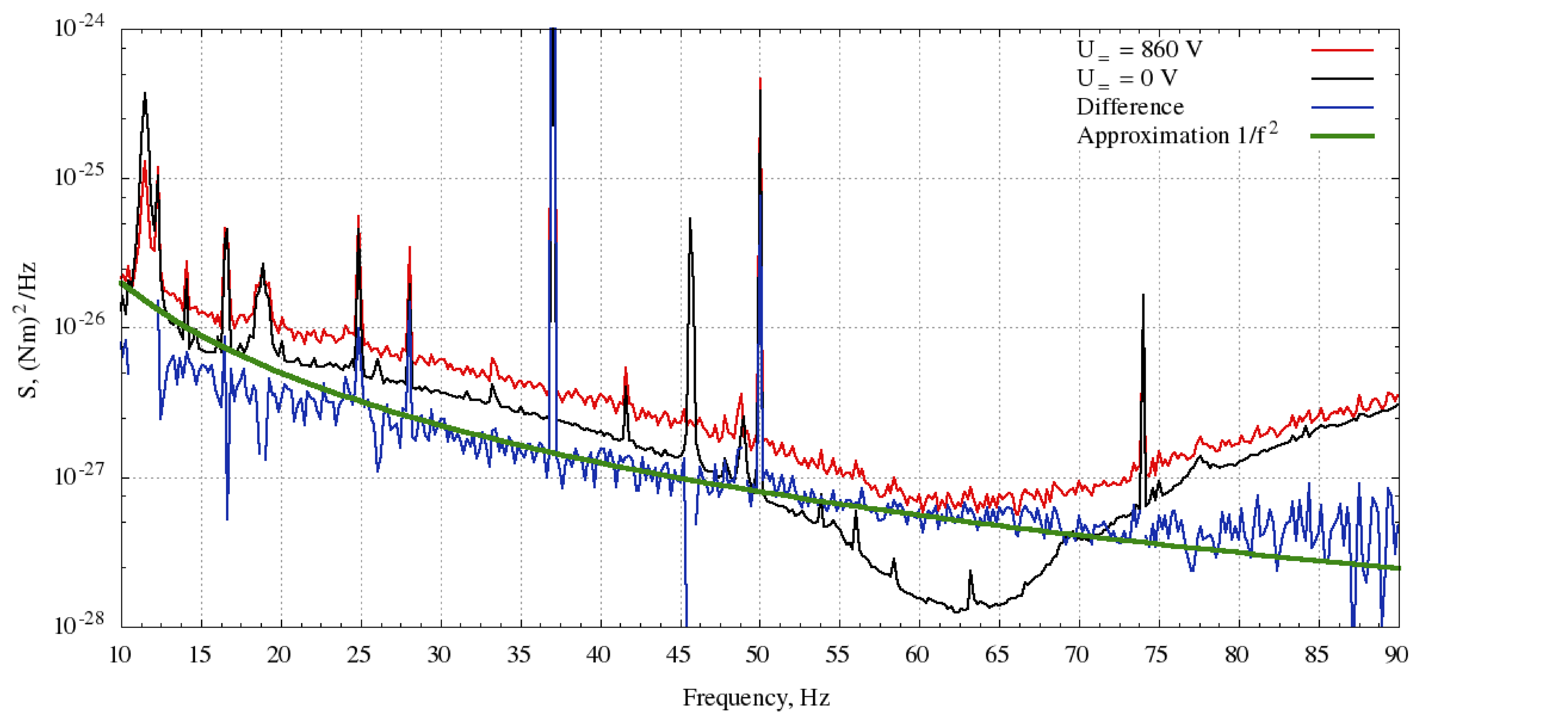

Figure 6 : Power spectrum density of moment of fluctuating force: $U_{=} = 860V$ - red, $U_{=} = 0V$ - black, difference between these spectrum densities - blue.

Conclusions

Experimental setup has been upgraded and the sensitivity close to thermal noise of the oscillator has been achieved in air at frequencies near $63Hz$. It has been shown that the electrostatic force between fused silica plate and the ESD changes with time. Numerical model which describes this time evolution has been developed. Results of numerical computation agree with experimental data. Additional noise has been observed when high voltage is being applied to the ESD. Thorough investigation of this result is in progress.
We plan to extend the numerical simulation by including noise model. Also we plan to develop simulation model for Advanced LIGO test mass and give an estimation of the charging noise level.

References

1. L.G. Prokhorov and V.P. Mitrofanov, Class. Quantum Grav., 27 (2011) 225014
2. D. Ugolini et al, Rev. Sci. Inst., 85 (2014) 034502
3. D.V. Koptsov et al., Instr. and Exp. Tech., 56(2) (2013) 215
4. J.A. Voorthuyzen, K. Keskin, P. Bergveld, Surface Science, 187(1) (1987) 201
5. P. Campsie, J. Hough, S. Rowan and G. D. Hammond, Submitted to Class. Quantum Grav., LIGO-P1300078-v2

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