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Effects of humidity on the interaction between a fused silica test mass and an electrostatic drive

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ABSTRACT

Interaction of a fused silica test mass with electric field of an electrostatic drive with interdigitated electrodes and influence of ambient air humidity on this interaction are investigated. The key element of the experimental setup is the fused silica torsional oscillator. Time dependent increase of the torque acting on the oscillator's plate after application of DC voltage to the drive is demonstrated. The torque relaxation is presumably caused by the redistribution of electric charges on the fused silica plate. The numerical model has been developed to compute the time evolution of the plate's surface charge distribution and the corresponding torque.

1. Introduction

Investigation of dielectric charging and transport of electric charges in dielectrics has a long history. Firstly, the interest was caused by a struggle with static electrification and its negative effects in industry, then by the development of various electret devices. In recent years, the problem of the time-dependent dielectric charging in radio frequency micromechanical system (MEMS) capacitive switches as well as in electrostatically actuated MEMS micromirrors is attracting more attention because the charging has significant impact on the device performance and leads to reduction of the reliability and the lifetime of these devices [1–3]. Electrostatic actuators are also used for control of dielectric mirrors in sensitive laser interferometers and advanced gravitational wave detectors [4,5]. The characteristic time of charge accumulation and charge decay can reach several years for materials with excellent insulating properties, such as fused silica SiO_2, placed in vacuum [6,7]. While bulk charging is not expected to be sensitive to environmental conditions, surface charging and surface electrical conduction are affected by ambient humidity [8]. Study of dielectric charging under different relative humidity levels allows deeper understanding of this process. Various experimental techniques including Kelvin probe force microscopy, measurement of the capacitance–voltage characteristic, discharge current transient method and others are employed to study dielectric charging phenomena and surface conduction [8–10].

In this paper, we present results of experimental investigations of time dependent response of a fused silica torsional mechanical oscillator to a step-like voltage applied to the nearby electrostatic drive (ESD) with interdigitated electrodes. This transient is associated with redistribution and accumulation of electric charges on the fused silica plate of the oscillator. The charge accumulates in peaks mirroring the electrode pattern. Measurements were carried out under different relative humidity levels. Finite element simulation of charge migration on the surface of the plate and its interaction with the electrostatic drive has shown a good agreement with the observed behavior of the oscillator.

2. Experimental setup

The experimental setup, specially developed to investigate the interaction between fused silica plate and the ESD is presented in Fig. 1. The fused silica test mass is a rectangular plate ($25.4 \times 10 \times 2.5$ mm^3) welded via thin fused silica fibers to a rectangular frame so that a monolithic torsional oscillator is formed. Two FR4 glass epoxy laminate plates with gold coated interdigitated electrodes form two electrostatic drives. They are placed parallel to the plate of the oscillator at a distance of about 1.5 mm. The interdigitated electrodes are formed by an array of strips 1 mm wide with period of 2 mm alternatively at the electric potentials $U_{DC/AC}$ and 0 (grounded). Inhomogeneous electric field created by the electrodes of the ESD produces the electrostatic force acting on the

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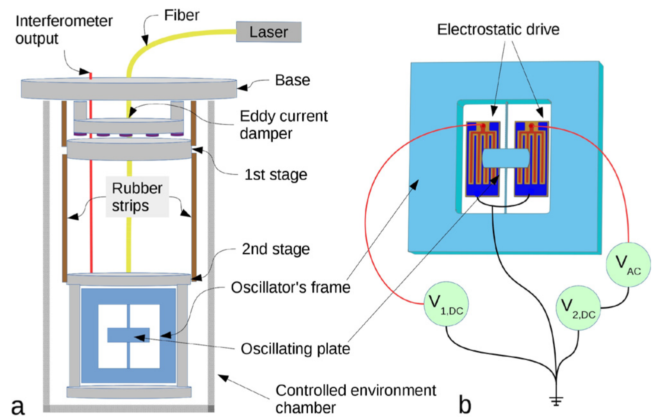

Fig. 1. Schematic of the experimental setup. a) Double pendulum suspension of the frame with the oscillator. b) Electrostatic drives with voltage application scheme.

dielectric plate. Each ESD is mounted on an underlying aluminum baseplate and has an independent voltage source so that DC, AC or DC+AC voltages can be applied to it. The ESD's baseplates can be moved to adjust the distance between each ESD and the oscillator's plate in order to compensate the action of the ESDs when DC voltage is applied to them and thus reduce the twist of the oscillator's plate. Further fine tuning is achieved by slightly varying the difference between DC voltages applied to the ESDs. The oscillator and the ESDs are surrounded by grounded metal parts that form an electrostatic shield. The torsional oscillator's resonant frequency $f_0 = 63.13$ Hz, the quality factor $Q \approx 10^6$ in vacuum and $Q \approx 2100$ in air. The twist angle is measured with a specially designed Michelson interferometer. The back surface of the oscillator's plate has a reflective dielectric coating. It forms two moving in counter-phase mirrors of this interferometer [11]. The oscillator, the ESD plates and the interferometer are mounted on a slab that is suspended as a double pendulum by rubber strips. Each stage is suspended using 3 strips with sizes of $20 \times 4 \times 80$ mm^3 for the upper stage and $20 \times 4 \times 200$ mm^3 for the lower stage. The upper stage of the double pendulum is damped by means of an eddy current damper in order to provide seismic isolation. The system is placed in the humidity controlled chamber. The sensitivity of the experimental setup at frequencies near the resonant frequency of the oscillator is found to be close to the limit determined by the torque thermal fluctuations with power spectral density $S_M(\omega) \approx 10^{-28}$ $(\mathrm{N\,m})^2/\mathrm{Hz}$.

Measurements were carried out at room temperature at different relative humidity levels h ($30\% \leqslant RH \leqslant 60\%$). Before each measurement the sample was kept in the closed chamber for a day or more in order to achieve equilibrium between humid air and the sample. The absence of air breakdown was controlled by monitoring the noise spectrum of the torque acting on the oscillator.

The electrostatic force exerted by the ESD on the fused silica plate produces a torque M turning the plate. It can be related to the voltage U applied to the electrodes [12]:

$$M_1 = \frac{1}{2}\frac{dC}{d\theta}U^2 = AU^2, \tag{1}$$

where C is the capacitance between the electrodes at potential U and grounded electrodes of the ESD, θ is the oscillator's plate twist angle, A is the constant of proportionality.

An additional torque is produced if the fused silica plate of the oscillator is charged. It can be written as [13]:

$$M_2 = BU + M_{im}, \tag{2}$$

where the constant of proportionality B and M_{im} depend on the amount and distribution of the charge that is present on the plate as well as on the geometry of the system, i.e. position of the ESD, the plate, surrounding metal and dielectric objects. The term M_{im} is associated with the electrostatic image force and is considered negligible in the further analysis. Redistribution and accumulation of electric charges on the fused silica plate of the oscillator alters the second term of the full torque $M = M_1 + M_2$. In the experiment, AC voltage ($U_{AC}\cos\omega t$) with $U_{AC} = 0$–20 V and DC voltage $U_{DC} = 0$–1000 V are applied to the electrodes of the ESD, and the amplitude of the twist angle θ_ω of the oscillator's plate at the frequency $\omega = 2\pi$ 36 Hz is monitored. The amplitude of the torque $M_\omega = M_{\omega,1} + M_{\omega,2}$ at the frequency ω is calculated using the relationship

$$\theta_\omega = K(\omega)M_\omega, \tag{3}$$

where $K(\omega)$ is a modulus of mechanical susceptibility of the torsional oscillator which describes its angular response θ_ω to the torque M_ω at the frequency ω:

$$K(\omega)^{-1} = J\left((\omega^2 - \omega_0^2)^2 + \omega^2\omega_0^2/Q^2\right)^{1/2},$$

where J – moment of inertia of the torsional oscillator's plate, $\omega_0 = 2\pi\ f_0$ – resonant angular frequency, Q – quality factor.

In the experiment, U_{DC} is applied to both ESDs in order to compensate their action. U_{AC} is applied only to the first ESD and produces the torque with the amplitude

$$M_\omega = 2AU_{DC}U_{AC} + BU_{AC}. \tag{4}$$

A change of the charge distribution on the fused silica plate changes the coefficient B and therefore the torque M_ω.

3. Results of measurements

The constant of proportionality A in Eq. (1) can be determined from the dependence of the amplitude of the torque M_ω on U_{AC}. If the charge on the surface of the oscillator's plate is small, i.e. $M_{\omega,1} \gg M_{\omega,2}$,

$$M_\omega \approx 2AU_{DC}U_{AC}, \tag{5}$$

and A can be determined from the measurement of M_ω as a function of U_{AC} provided that U_{DC} is constant. The value of A was found to be $\approx 2.5 \cdot 10^{-14}$ $\mathrm{N\,m/V^2}$.

The time evolution of the torque $M_\omega(t)$ calculated from the measured amplitude of the forced oscillations at the frequency $\omega = 2\pi$ 36 Hz according to Eq. (3) is shown in Fig. 2. U_{AC} is applied to one of the ESDs during all the time at all stages of the measurement. At the first stage U_{DC} is switched off in order to measure the initial level of the torque due to preexisting charge distribution. At the next stage U_{DC} is applied to both ESDs. At the 3rd stage the U_{DC} is switched off.