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Possibilities for measurement and compensation of stray DC electric fields acting on drag-free test masses

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Abstract

DC electric fields can combine with test mass charging and thermal dielectric voltage noise to create significant force noise acting on the drag-free test masses in the Laser Interferometer Space Antenna (LISA) gravitational wave mission. This paper proposes a simple technique to measure and compensate average stray DC potentials at the mV level, yielding substantial reduction in this source of force noise. We discuss the attainable resolution for both flight and ground based experiments.

Keywords: Gravitational waves; Free-fall; Electrostatics; DC electric field; LISA; Space experiments

1. Introduction

In the envisioned design of the gravitational wave mission LISA, capacitive sensors will provide the readout of the relative position of the satellites with respect to the freely flying test masses, which serve both as interferometry end mirrors and drag-free orbit references (Bender et al., 2000). A drawback of electrostatic sensors is that the combined needs of high precision ($\approx \mathrm{nm}/\sqrt{\mathrm{Hz}}$) and low electrostatic force gradients require a small distance (or gap, d) between the test mass and sensing electrodes. This need for proximity introduces a number of less easily characterized short-range force effects, electrostatic and otherwise, which grow with decreasing gap and can dominate the low frequency test mass acceleration noise. An important example is DC electric fields, which produce both force gradients (or "stiffness") increasing as d^{-3} and, coupled with charging and dielectric noise, force noise proportional to, respectively, d^{-1} and d^{-2}, assuming in the second case a dielectric loss angle $\delta \propto d^{-1}$ (Speake et al., 1999). Though the current sensor design for the European LISA demonstrator flight experiment LTP (Vitale, 2002) calls for relatively large 4 mm gaps along the sensitive x axis[1] in order to limit these short-range effects (Weber et al., 2002), DC fields are still expected to be a significant noise source.

Stray DC fields, related to spatially varying DC surface potentials known as patch fields, can arise from the different work function of domains exposing different crystalline facets. These fields statistically average over the small grains, which for gold surfaces can be micron size and produce RMS surface potential variations of order 1 mV on mm length scales (Camp et al., 1992). These are not likely to be a significant problem for the designed sensor, shown schematically in Fig. 1, where 4 mm x axis gaps provide distance for the fields and gradients to fall off, as well as an effective dilution of the smaller length scale variations (Speake, 1996). Potentially more dangerous are patch fields

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[1] The test masses in both LISA and LTP have a single preferred measurement axis, referred to here as x, in which it is essential to minimize the stray force disturbance.

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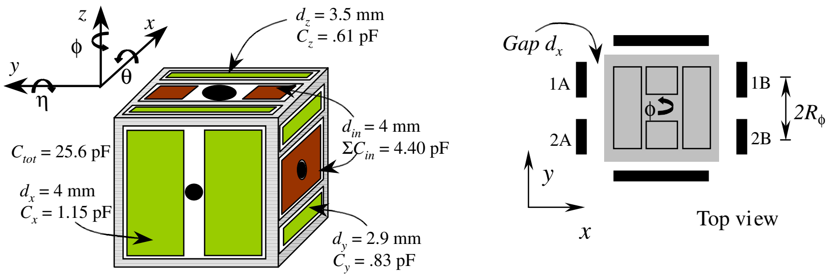

Fig. 1. Schematic of proposed capacitive sensor, with capacitance and gap values, adapted from Weber et al. (2002). The injection electrodes used to provide the sensing bias are darkly shaded, the sensing electrodes are medium gray, and grounded guard ring surfaces are light gray. The planned test mass is a 46 mm, 2 kg Au/Pt cube.

with relatively large coherence lengths, caused by surface contamination from the assembly and from material outgassing over a long mission. Noise models have assumed typical average whole electrode DC biases δV of order 100 mV (Weber et al., 2002).

Electrostatic actuation circuitry, to be integrated with the sensor for application of forces using audio frequency modulated voltages, will also allow direct application of DC voltages to the sensing electrodes. We analyze here, as a way to reduce the total acceleration noise caused by stray DC biases, the use of applied actuation voltages to first measure the average biases and then compensate to make the average DC potential zero. The electrostatic model considered here considers each electrode as having a single uniform potential, without spatial variation. This much simplified analysis addresses what we can actually change with a single applied voltage per electrode, the average DC potential. This approach is still relevant, as the likely dominant effect, the interaction of DC fields with the noisy test mass charge, is realistically parametrized, and thus curable, by the average DC potential difference between electrodes on opposing sides of the test mass. We start with a description of the noise sources related to stray DC biases, then turn to the techniques for measuring and balancing them, both in flight and on the ground.

2. Nature of the problem: noisy forces arising from DC fields

We analyze here the simplified model of the sensor in Fig. 2. Four x sensing electrodes, opposing pairs 1A/1B and 2A/2B, face the test mass along the x axis. Functionally, differential measurements of the two capacitor pairs are combined to yield the test mass x translational and ϕ rotational displacements (Weber et al., 2002). Assigning electrode potentials V_j and an accumulated test mass charge q, the instantaneous x force component F_x and test mass potential V_M can be expressed

$$F_x = \frac{1}{2}\sum_i \frac{\partial C_i}{\partial x}(V_i - V_M)^2 \tag{1}$$

$$V_M = \frac{q}{C_T} + \frac{1}{C_T}\sum_j C_j V_j \tag{2}$$

C_T is the total capacitance of the test mass to all sensor surfaces, including the four x-electrodes, the z-electrodes (shown in dark gray and to be used for applying a measurement bias V_Δ in Section 3), and all other electrode surfaces, to be lumped together as C_g, including the injection electrodes, y-electrodes, and grounded guard ring surfaces (seen in Fig. 1). We sum here in principle over all sensor conducting surfaces i, including individual surface domains, that can have a unique electrostatic potential. In our simplified model where the potential is uniform over each electrode, this sum will reduce to a sum over electrodes. Additionally, for a centered TM, the derivative $\frac{\partial C_i}{\partial x}$ will have non-zero contributions only from the 4 x sensing electrodes.

While the x electrodes will nominally be held at DC ground by the sensing/actuation circuitry (Weber et al., 2002), we consider here for each a non-zero V_i caused by

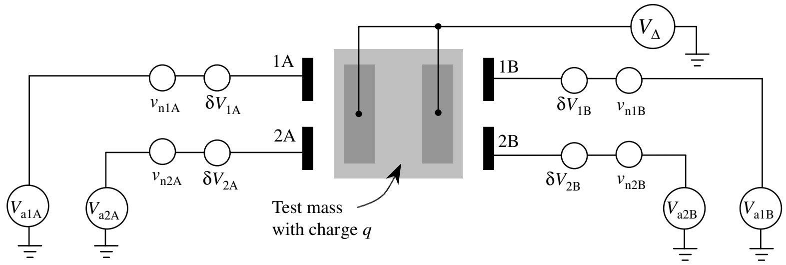

Fig. 2. Schematic of the simplified, four electrode electrostatic model and measurement technique analyzed here. Stray DC biases, dielectric noise, and test mass charge are denoted δV_i, v_{ni}, and q. In the main measurement described in the text, a modulated bias V_Δ is applied to the test mass via the z electrodes. Actuation voltages V_{ai} can be applied to compensate the δV_i and can also modulate the electrode voltages in other measurements.