

Test Mass Emulator for ground checkout of electrostatic space accelerometers

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ABSTRACT

Electrostatic accelerometers and inertial references are key instruments for space geodesy and fundamental physics missions, where the motion of a free-falling test mass must be sensed and controlled with extremely high accuracy. This paper presents the preliminary design of a Test Mass Emulator (TME) intended for the ground checkout of the front-end electronics and control algorithms of electrostatic space accelerometers, with specific reference to the Gravitational Reference Sensor of the LISA mission. The emulator is conceived as part of a hardware-in-the-loop setup in which the real electrode housing is replaced by coupled variable capacitors able to reproduce the differential currents expected from the motion of the test mass. The design is supported by FEM simulations aimed at minimizing crosstalk between adjacent electrode pairs and assessing the impact of thermo-elastic expansion. Preliminary characterization of the selected piezo-walk linear actuators shows that the required dynamic motion can be achieved, with positioning errors below about 200 nm under representative operating conditions. These results support the feasibility of the proposed TME concept as a functional verification tool for LISA and, more generally, for any electrostatic space accelerometers.

Keywords: Space geodesy, electrostatic accelerometers, LISA mission, variable capacitors

1. INTRODUCTION

Space geodesy requires accelerometers or inertial references with readout noise levels of the order of a few tens of $\text{pm s}^{-2} \text{Hz}^{-1/2}$ over a frequency band ranging from fractions of a mHz to a few Hz. Such performance has been achieved by electrostatic suspension systems flown on several geodetic missions, including CHAMP, GOCE, GRACE and GRACE-FO, which have provided the best acceleration noise levels in low Earth orbit.^{1–4} Similar technologies have also been employed in the Gravity Probe B mission,⁵ aimed at testing in space the equivalence principle. With the purpose of preparing future space missions for the detection of Gravitational Waves (GW), the Gravitational Reference Sensor (GRS) of *LISA Pathfinder* (LPF) achieved a noise level more than two orders of magnitude lower, although in a less severe environment than the low Earth orbit of geodetic missions. Nevertheless, even with a degradation of its performance in low Earth orbit, the GRS concept could provide significant improvements for space geodesy.⁶

These instruments typically consist of a geodesic inertial reference test mass, which should be subjected only to gravitational and electrostatic forces. The test mass is surrounded by a set of electrodes housed in a cage, used both to detect its position and to apply electrostatic forces that compensate for non-gravitational disturbances acting on the host spacecraft. The electrodes and the test-mass surfaces form capacitive displacement sensors, while the geometry of the surrounding cage defines the axes along which linear accelerations are measured and those about which angular accelerations are monitored. In closed-loop operation, acceleration is measured through a null method, by evaluating the electrostatic force required to keep the TM in its central position. The sensitivity of the accelerometer increases with the mass of the inertial body and is inversely proportional to its stiffness. To avoid seismic noise during ground testing, the ultimate measurement performance of the reference system before launch is usually assessed either by suspending the test mass from a pendulum,⁷ when the mass is too large, or by electrostatically levitating it.³ For the remaining constrained axes, or in the case of a heavy

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inertial mass, a possible test environment is provided by drop tower facilities, such as the Bremen Drop Tower at the ZARM Institute or, more recently, the Einstein Elevator facility at Leibniz University Hannover.

The test bed whose design is presented in this paper is not intended to investigate the full performance of a high-sensitivity electrostatic space accelerometer. Its objective is instead to provide a functional test of the front-end electronics at integration level, as well as to assess the effectiveness of the control algorithms in managing nominal and critical events during the mission. The paper focuses on the development of a test bed for the GRS of the LISA mission, which is characterized by a demanding set of requirements, although the same concept could be adapted to other electrostatic space accelerometers. Moreover, only the sensing section is discussed here, even though the test bed under development is also intended to digitize the actuation voltages applied to the electrodes and transmit them to a Real Time Simulator (RTS). The latter will perform a complete simulation of the accelerometer test mass dynamics and of the spacecraft motion.

In the following sections, the main features and objectives of the LISA GRS are first outlined in order to provide the framework of the activity. The working principle and goals of the Test Mass Emulator are then presented, together with some insight about the design that is taking place. Finally, preliminary tests performed on the actuators are discussed, with the aim of verifying the feasibility of the proposed approach.

2. GRAVITATIONAL REFERENCE SENSOR

LISA, the Laser Interferometric Space Antenna for gravitational waves, is one of ESA's L3-class missions,⁸ with launch currently expected in 2035. The mission will consist of a triangular constellation with arms 2.5 Mkm long. Each spacecraft will host two free-falling test masses (TMs), which act as geodesic references. Their relative motion will be tracked by interferometry along the constellation arms in order to detect the tidal effects produced by passing gravitational waves. At frequencies below 4 mHz, the sensitivity of LISA is limited by spurious accelerations of the TMs, which the ESA *LISA Pathfinder* mission demonstrated to be of the order of $2 \text{ fm}\cdot\text{s}^{-2}\cdot\text{Hz}^{-1/2}$.⁹ The GRS of the LISA payload will accommodate the TM, the electrostatic cage with its electrodes, the UV source used to discharge the TM, the Front End Electronics (FEE), and the retractable plunger devoted to holding, releasing and/or recovering the test mass. The electrodes embedded in the Electrode Housing (EH) around the TM form 12 plane-parallel capacitors, two on each face of the TM. Fig. 1 shows the TM together with the surrounding electrodes. The capacitances associated with opposite electrodes are read differentially by means of a capacitive bridge circuit. This allows the position and attitude of the inertial sensor to be monitored over six degrees of freedom. The same electrodes are also used to apply electrostatic forces. In order to further reduce mechanical noise, the TM is not connected to ground to fix its electric potential and drain the excess charge produced by cosmic rays. Instead, its potential is electrostatically induced by an additional set of electrodes, whose voltage is modulated at a frequency of about 100 kHz, so that the oscillating TM potential reaches a maximum value of approximately 0.6 V.

The TM is a gold/platinum alloy cube with a 46 mm edge and a mass slightly below 2 kg. It exhibits a weak diamagnetic behavior, with an absolute magnetic susceptibility of about 2×10^{-5} . Each face of the TM forms two capacitances with pairs of identical planar electrodes embedded in the surrounding cage, namely the EH. When the TM is centered, the gap between the cube surface and the electrodes is approximately 4 mm. The main functions of the FEE are to sense the cube position, to generate the actuation voltages applied to the same sensing electrodes, and to induce an $\approx 100 \text{ kHz}$ potential on the TM through a set of “*injection*” electrodes. The sensing circuit, including the input from the actuation circuit, is schematically shown in Fig. 1.¹⁰ The differential capacitance readout is performed by inserting the capacitors formed with the TM surface into a capacitive bridge coupled to a differential transformer. The inductance of the transformer windings is about 4 mH and, together with the capacitance $C_P \approx 633 \text{ pF}$, forms a resonant circuit at approximately 100 kHz, corresponding to the frequency of the potential induced on the TM. The capacitances formed by the electrodes and the TM faces have similar values of about $1 \text{ pF} \ll C_P$. The rectangular electrodes on the Y and Z faces have an area of about $7 \text{ mm} \times 37 \text{ mm}$, whereas the area of the X electrode is twice as large. However, the gap for the X electrodes is 4 mm, while the gaps for the electrodes on the Y and Z faces are 2.9 mm and 3.5 mm, respectively.

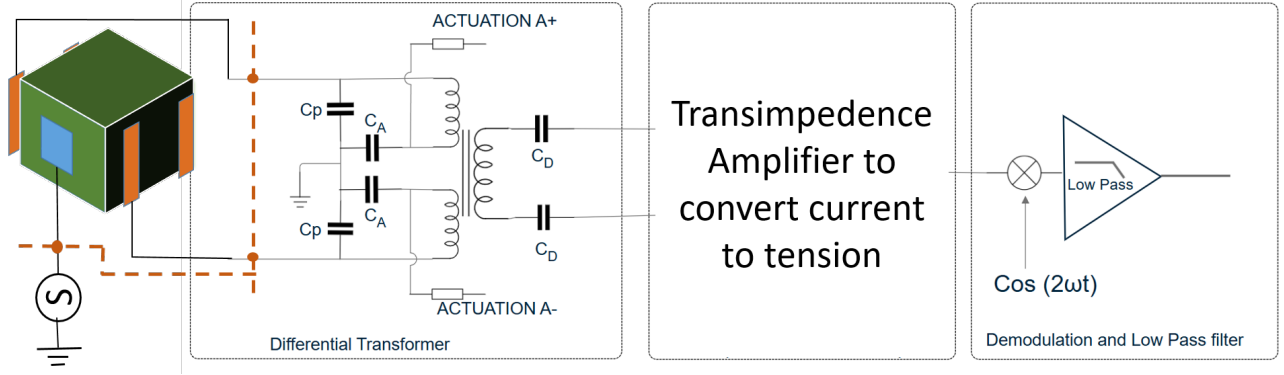


Figure 1. Schematic of the circuit used to read the TM position. The circuit measures the differential capacitance of a pair of opposite electrodes. The TM is maintained at a potential oscillating at approximately 100 kHz by means of the injection electrodes. A capacitive bridge coupled to a differential transformer forms a resonant circuit tuned to the TM-potential frequency, producing a differential current in the inductors that is proportional to the TM displacement with respect to the sensing electrodes. The current in the secondary circuit of the transformer is converted into a voltage by a trans-impedance amplifier and filter. In the third block, the signal is demodulated by a lock-in amplifier and low-pass filtered. The three orange dots indicate the connection points required for the TME.

3. TEST MASS EMULATOR DESIGN

In the LISA mission, the inertial reference provided by the TM is maintained in drag-free conditions through electrostatic actuation and a feedback system acting on the spacecraft thrusters. These elements are integrated within the Drag Free Attitude Control System (DFACS). Within this control chain, the main electrical interface to the EH is the FEE, which includes the circuit shown in Fig. 1. The DFACS functions must be validated on ground before launch. Testing the electronics associated with each degree of freedom, the control logic, and specific mission events, such as the release of the TM after orbit insertion or the effects of micrometeorite impacts, requires a representative experimental environment. However, canceling the terrestrial gravitational field by suspending the mass would constrain some degrees of freedom and, in the case of the nearly 2 kg LISA TM, electrostatic levitation would not be feasible as it was, for example, for the accelerometers of the GRACE mission.³ A different approach must therefore be adopted, in which the FEE is made to operate as if it were connected to the actual GRS. An hardware-in-the-loop approach has been adopted connecting the FEE with an emulator reproducing the kinetics of the real TM and with the DFACS control logic behind it.

The FEE will provide two electrical contacts for each pair of electrodes, together with one contact for the 100 kHz injection voltage. When the capacitive bridge is exactly balanced, corresponding to a TM centered with respect to the two electrodes, the current amplitudes in the two windings of the differential transformer are equal and the voltage at the secondary winding is zero. A bridge unbalance generates a difference between the current amplitudes, proportional to the unbalance of the two complementary capacitances and, consequently, to the TM displacement. For the sensing section, the purpose of the *emulator* is to reproduce, on the two primary windings, the same current amplitudes that would be produced by the real LISA GRS for any given TM position. Unlike the solution adopted for testing the LPF GRS, where a current source proportional to the capacitance unbalance was implemented, the approach proposed here relies on variable capacitors. Once connected to the FEE terminals, these capacitors are intended to generate the same differential capacitance and the same currents in the transformer primary windings. A similar strategy was previously used for the Gravity Probe B mission.⁵

To limit the complexity and cost of the emulator, the approach under investigation does not aim to implement 12 independent capacitors reproducing exactly the configuration of the EH. Indeed, when the TM undergoes pure translations, the distances between the TM and each pair of coupled electrodes do not vary independently, but rather in a complementary way. One TM surface approaches one electrode while moving away from the opposite electrode by the same amount. Nevertheless, since the capacitances are inversely proportional to the face-to-electrode distance, their variations are not themselves complementary. For this reason, the proposed baseline for the TME consists of six coupled variable capacitors, each made of two movable electrodes facing a fixed conductor whose potential oscillates at about 100 kHz and represents the TM. Each pair of electrodes is driven

by the same linear actuator. Therefore, when one electrode is moved closer to the fixed conductor, producing a nonlinear increase of the capacitance, the opposite electrode moves away by the same amount, producing a nonlinear decrease of the capacitance, as occurs for a pure translation of the TM in the GRS. At present, the baseline design assumes electrodes with the same shape and surface area as those of the EH. However, the actual motion of the TM inside the EH also includes complex roto-translations, which make the capacitances deviate from the ideal plane-parallel case. In principle, the TME cannot reproduce this capacitance variation exactly. The schematic representation in Fig. 2 illustrates the correspondence between the motion of the TM inside the GRS and the emulator concept under development. Nevertheless, since the goal of the TME is to provide the correct electrical current in the differential transformer, it can be shown that this objective can also be achieved with a set of coupled plane-parallel variable capacitors.

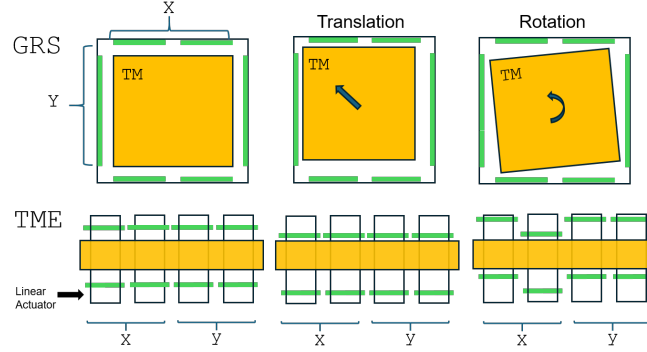


Figure 2. Schematic comparison between the TM motion inside the EH and the operating principle of the TME. In the upper part, the TM, represented by the orange square, is shown inside the EH and surrounded by the electrodes used, for instance, to apply forces and monitor the position of the X and Y faces of the TM, shown as green segments. In the lower part, the TME is represented as pairs of electrodes, again shown as green segments, forming plane-parallel capacitors with a fixed conductor, represented by the orange rectangle, whose potential varies as the TM potential. a) When the TM is centered in the EH, the electrodes facing the central conductor are equidistant. If their surfaces are the same as in the EH, the gap is also the same and the capacitance difference is zero. b) For pure TM translations, the electrodes are displaced in pairs so as to reproduce the same gap and capacitance difference as in the EH. c) For a TM rotation, the TME electrode pairs move in an alternate way to reproduce the capacitance differences generated in the EH, with the limitation that the electrodes cannot rotate and therefore assume intermediate positions.

3.1 The emulating signal

When the capacitance C_P and the inductance of the primary circuit are selected so as to resonate at 100 kHz, namely $C_P L = \frac{1}{\omega^2} = \frac{1}{(2\pi \times 100 \text{ kHz})^2}$, and the winding resistance R_L satisfies $(C_P + C_S)^2 \omega^2 R_L^2 \ll 1$, the expression of the current difference through the primary windings takes a simple form, depending on the capacitance unbalance:

$$\Delta I_L(t) \simeq \omega \Delta C_S V_{TM} \sin(\omega t) \quad (1)$$

where ΔC_S is the capacitance difference between the sensing electrodes, V_{TM} is the amplitude of the oscillating TM potential, and $\omega = 2\pi f$ is the angular frequency. Fig. 3 shows the amplitude of the current difference for pure translations along the three coordinate axes.

3.2 Test Mass electrical connection

The TME will replace the electrode pairs of the GRS; therefore, Eq. 1 will also drive its design and operating principle. In the GRS, the required acceleration sensitivity is so demanding that the TM cannot be electrically contacted to fix its electric potential, not even by means of an extremely thin, low-mass wire. Its potential is therefore induced by non-contact injection electrodes. Conversely, in the TME, the mock-up of the TM can be electrically connected to the injection voltage provided by the FEE, which greatly simplifies the design of the emulator.

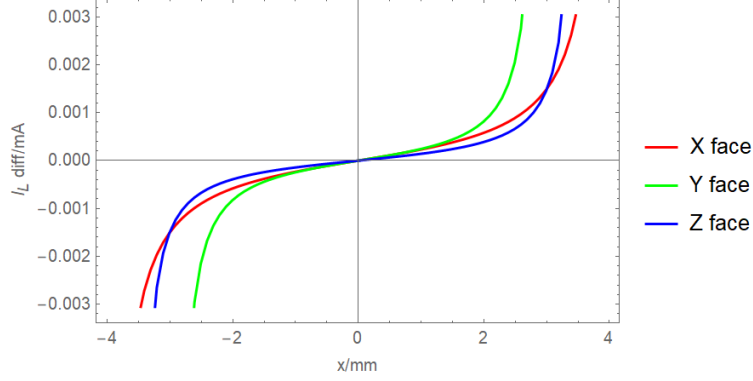


Figure 3. Current difference through the transformer primary windings for pure translations of the TM along the coordinate axes, each associated with a face of the cubic TM. Zero displacement corresponds to the centered TM. Around the central position, the current difference is nearly linear, while at larger displacements it approaches an almost cubic behavior.

In the GRS, the potential appearing in Eq. 1 depends on the capacitances between the TM and all the surrounding sensing electrodes, as well as on the capacitances with nearby conductors, such as the Electrode Housing (EH). As a consequence, the TM potential, V_{TM} , varies with the position of the TM inside the EH. In the emulator, instead, this potential will be kept constant, making the current difference associated with each electrode pair independent of the other five pairs.

However, the injection voltage provided by the FEE has an amplitude of about 4.9 V. In order to reduce the TM voltage to the expected amplitude of approximately 0.6 V for a centered TM in the GRS, a capacitive voltage divider will be used to connect the test mass to the injection voltage. This capacitive interface will also preserve the phase of the emulator TM potential with respect to that expected in the GRS.

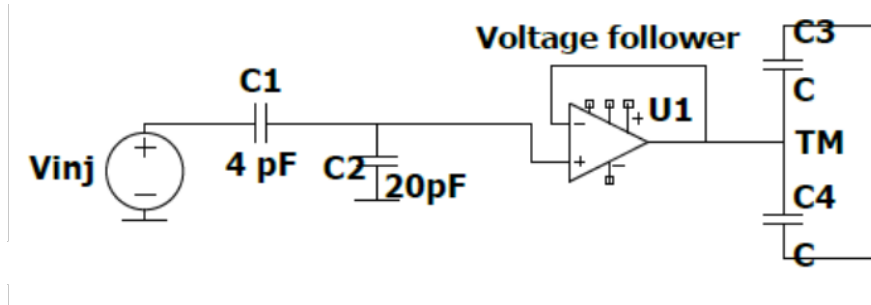


Figure 4. Capacitive voltage divider used to scale the injection voltage from 4.9 V down to approximately 0.6 V, while providing an impedance of about 3 M Ω at 100 kHz. A voltage buffer will also be included to ensure complete decoupling.

3.3 Cross-talk and stray effects

The design of the TME was supported by a FEM model developed in COMSOLTM. The model was used to define a configuration that minimizes the crosstalk between electrode pairs and to assess the effect of thermal expansion on the differential current.

3.3.1 Crosstalk

As shown in Fig. 5, the TM in the emulator consists of a pair of 30 cm long conductive bars, along which 6 electrode pairs, three for each bar, are arranged. Each pair is connected to a linear actuator.

This configuration may introduce crosstalk between adjacent electrode pairs, namely an apparent capacitance variation in a stationary sensing electrode caused by the displacement of neighboring electrodes. Such crosstalk can be reduced by suitable guard-ring geometries, which limit the stray electric fields associated with the sensing electrodes. Using the FEM model, two possible guard-ring configurations were compared: a thick conductive

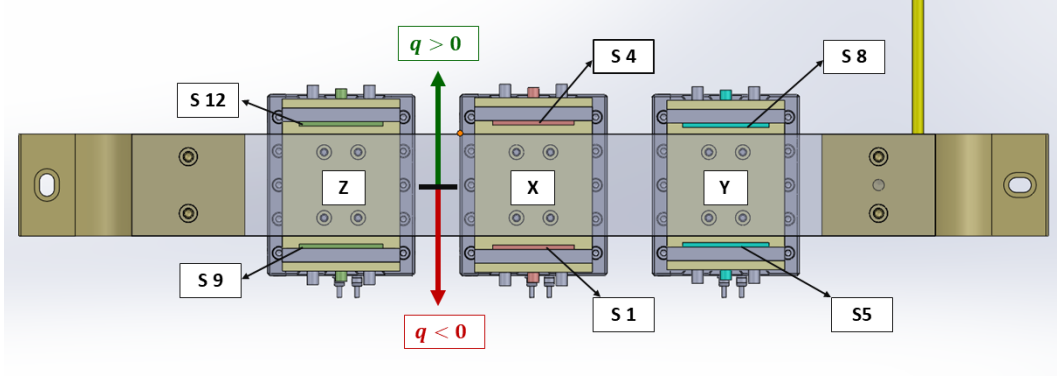


Figure 5. Top-view schematic of the electrode architecture and translation actuators.

film surrounding the sensing electrode, and a bulk conductive cage enclosing the sensing electrode while leaving exposed only the electrode face oriented toward the TM surface. As shown in Fig. 6, the thick-film solution does not fully suppress the crosstalk, since stray fields can still couple through the rear faces of adjacent electrodes.

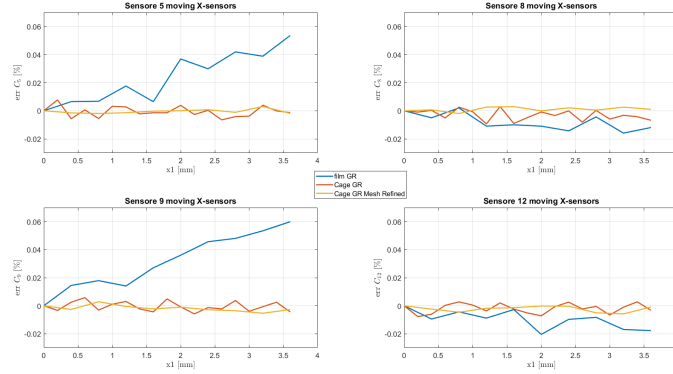


Figure 6. Comparison of the capacitance error on adjacent sensors due to crosstalk for different guard-ring configurations. The central X electrodes are displaced so that electrode S1 moves closer to the TM, while S4 moves away from it. The capacitances of the four adjacent electrodes are computed with the FEM model and reported in the four panels. The blue curves correspond to the thick-film guard rings and clearly show crosstalk from the X electrode pair. The bulk guard-ring configuration removes this effect within the resolution of the FEM computation. A simulation with a finer mesh was also performed to verify that the results are not mesh-dependent.

3.3.2 Thermo-elastic expansion

The TME will be hosted inside a specially designed thermo-vacuum chamber in order to minimize the influence of environmental parameters on the relative permittivity and, consequently, on the capacitance values of the electrodes, while also ensuring fine temperature control. To this end, the temperature of the TME will be regulated by a thermoelectric heater/cooler. The same type of TEC device has already demonstrated temperature oscillations below 0.02 °C in a thermo-vacuum chamber containing a device under control with a volume comparable to that of the TME.

The FEM model has shown that the coefficients of thermal expansion (CTEs) of the materials to be used, namely electrical conductors for the electrodes and guard rings, and insulating ceramics for the supports, are not particularly critical for the performance required in a hardware-in-the-loop configuration aimed at the functional testing of the electronics and control algorithms. The sensitivity to thermal expansion is strongly reduced by the symmetric design of the electrode-pair supports. In the presence of thermal expansion, this geometry produces an equivalent motion of the coupled electrodes either toward or away from the TM, without significantly changing the differential capacitance ΔC and, according to Eq. 1, the differential current. The variation of ΔC has been estimated to lie in the range of a few hundred aF at mHz frequencies, whereas the accuracy of the positioning

will imply a repeatability of fF. The studies to define the final accuracy of the TME are being conducted at this time.

4. LINEAR ACTUATORS CHARACTERIZATION

As discussed in the previous section, the TME electrodes will be connected in pairs to linear actuators, so that each pair can be displaced in a coupled configuration. The actuator travel range must be approximately ± 4 mm in order to cover the full translation range of the TM, while the required positioning accuracy depends on the TM-positioning requirements to be emulated. These requirements are currently being defined with ESA, since the activity is part of the development of the GRS for the LISA mission.

Two relevant requirements concern: i) the discretization of the emulated TM position, which is related to the repeatability with which a given capacitance difference can be reproduced and, therefore, to the repeatability of the electrode positioning by the actuators in a dynamic condition; and ii) the rate at which the capacitance, and hence the electrode position, can be updated to emulate either linear translations or rotations of the TM. The target repeatability is of the order of tens of nm, corresponding to several hundreds of aF in terms of capacitance difference.

Regarding the speed to be emulated, a reasonable starting point is provided by the requirements adopted for the LISA Pathfinder mission.¹¹ The most demanding condition in terms of linear and angular momentum is expected to occur during TM release, when the plunger holding the TM is retracted and the mass is left to evolve freely. Even if the release is designed to be as symmetric and controlled as possible, it will impart both linear and angular momentum to the TM. These disturbances must then be compensated by the electrostatic actuation and control system, which drives the TM back toward the centered position. Accurately emulating this phase is therefore essential for testing the DFACS control logic and the FEE under the most demanding operating conditions.

The translation speed to be reproduced is expected to reach values as high as $15 \mu\text{m/s}$, while the angular rate to be emulated may reach $500 \mu\text{rad/s}$. If the distance between the electrodes on each cube face is approximately 26 mm, this angular motion corresponds to an additional linear velocity of about $13 \mu\text{m/s}$ for each electrode. Therefore, the TME should be able to emulate linear velocities with a magnitude of about $30 \mu\text{m/s}$.

As schematically shown in Fig. 7, the TME will be part of a closed hardware-in-the-loop setup in which the FEE is disconnected from the GRS and connected to the TME. The FEE reads the capacitance unbalance and, therefore, the emulated TM position. In response, it provides the high voltages computed by the DFACS control logic to generate the electrostatic actuation forces. These voltages are acquired and digitized by the TME, then transmitted to the Real Time Simulator (RTS). Using a complete model of the TM dynamics, the RTS computes the electrostatic forces and update the TM position, which is then sent back to the TME, thus closing the loop. The RTS will update the TM position at 32 Hz, corresponding to one update every 31.25 ms, and the TME must follow this update rate. The FEE, instead, will update the actuation voltages at 8 Hz, corresponding to 125 ms. By combining the expected maximum speed to be reproduced by the TME with the position-update frequency, the linear actuator is required to displace the electrodes by approximately $1 \mu\text{m}$ within each update interval, while preserving the desired positioning accuracy.

The actuator selected to move the electrodes is the Physik Instrumente N-565.160 Piezowalk linear stage, which provides a travel range of 13 mm, larger than the required 4 mm. This actuator is based on the NEXACT[®] Piezo Stepping Drive, which enables long travel ranges with nanometer-scale resolution, making it well suited for this application. The actuator can operate either in open loop or in closed loop, using the integrated optical encoder. In closed-loop operation, repeatability and accuracy are determined by the encoder, whose resolution is 0.5 nm. According to the manufacturer specifications, the unidirectional repeatability is 50 nm, while the minimum incremental motion is 3 nm. In addition, the linear stage can reach velocities up to 10 mm/s and provide forces up to 20 N.

To verify the repeatability of the linear actuator and its capability to meet the velocity requirements, a series of positioning-repeatability and step-response tests was performed. The displacements were monitored using a SIOS D5000 interferometer with sub-nm resolution. The actuator characterization has already been presented

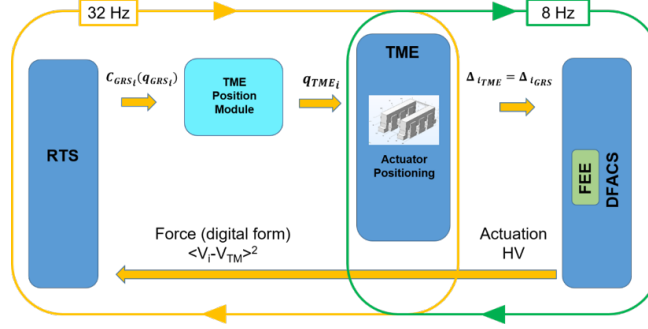


Figure 7. Schematic representation of the hardware-in-the-loop setup used to check out the FEE. The TME is one of the key elements of the loop: it provides the capacitance variation read by the FEE and digitizes the applied actuation voltages before transmitting them to the Real Time Simulator computer (RTS). The RTS will provide a full set of capacitance values vs. the TM, including those of the sensing electrodes and the conductors nearby. Then, the TME will convert them into a differential current value for each paired electrodes and will command, in an open loop, the configuration of the actuators in order to reproduce the differential currents.

in.¹² The static repeatability specified by the manufacturer was verified, and the step response was found to be sufficiently fast to perform μm -scale displacements at the required update frequency.

However, this is not sufficient to fully assess the positioning accuracy achievable when the actuator is driven by the updates sent by the RTS at a rate of 32 Hz and the actuators must therefore continuously adjust its position in dynamic conditions. To evaluate the positioning accuracy under these conditions, the linear actuator was programmed with a set of linear stepping ramps at the maximum expected pace, namely $30 \mu\text{m/s}$, while its position was monitored by the interferometer. In particular, the actuator was driven along a periodic triangular trajectory with a period of 260 s and a maximum stroke of 1.95 mm. For each step, the actuator moved at a speed six times larger than the maximum expected pace, thus allowing enough time to settle to the target position within the 31.25 ms duration of each update step.

Fig. 8 shows the difference between the commanded setpoint and the measured actuator position. The maximum error is about 200 nm. This value will be used to estimate the accuracy of the emulated electrical-current difference that the TME can provide to the FEE.

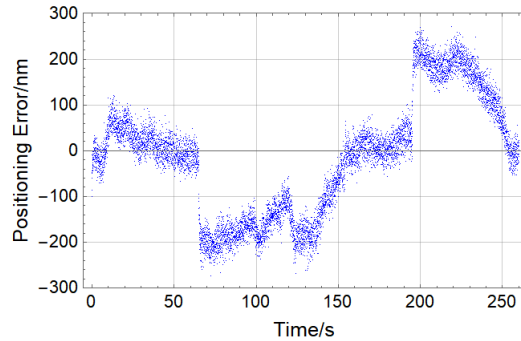


Figure 8. Positioning error of the PI NEXACT actuator when driven with a dynamic ramp at a speed of approximately $30 \mu\text{m/s}$.

5. CONCLUSIONS

The preliminary design steps of a GRS TM emulator have been presented. The emulator is intended to operate as a hardware-in-the-loop system for checking out the FEE functionality and the control algorithms implemented by the DFACS for the LISA mission. By fixing the electric potential of the TM and properly designing the guard rings with the support of a FEM model, it has been shown that the electrode pairs can be made independent and effectively immune to crosstalk. The piezo-walk linear actuators were further characterized to determine their

dynamic repeatability, which was found to remain below 200 nm in the most demanding condition, corresponding to the maximum expected pace of the TM in the GRS. The principle of the emulator can be applied to any space electrostatic accelerometer.

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