Double Degree of Freedom Pendulum Facility for the study of Weak Forces

R Stanga\textsuperscript{1,2}, L Marconi\textsuperscript{3,2}, C Grimani\textsuperscript{4,2}, M Bassan\textsuperscript{5,6}, G Pucacco\textsuperscript{5,6}, E Reali\textsuperscript{5,6}, R Simonetti\textsuperscript{6}, N Finetti\textsuperscript{7}

\textsuperscript{1} Dipartimento di Astronomia e Scienza dello Spazio, Università degli Studi di Firenze, Florence, Italy.
\textsuperscript{2} Istituto Nazionale di Fisica Nucleare, Florence, Italy.
\textsuperscript{3} Dipartimento di Fisica, Università degli Studi di Firenze, Florence, Italy.
\textsuperscript{4} Istituto di Fisica, Università degli studi di Urbino, Urbino, Italy.
\textsuperscript{5} Dipartimento di Fisica, Università degli studi di Roma Tor Vergata, Roma, Italy.
\textsuperscript{6} Istituto Nazionale di Fisica Nucleare, Roma Tor Vergata, Italy.
\textsuperscript{7} Dipartimento di Fisica, Università degli Studi dell’Aquila, L’Aquila, Italy and Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso, Gruppo Collegato dell’Aquila, Italy.

E-mail: marconi@fi.infn.it

Abstract. The LISA Test-Mass (TM) is sensitive to weak forces along all 6 Degrees of Freedom (DoFs). Extensive ground testing is required in order to evaluate the influence of crosstalks of various read-outs and actuators operating on different DoFs. To this purpose, and to better represent the flight conditions, we are developing a facility with 2 soft DoFs which consists of two stage roto-translational pendulum. This facility will measure the forces and stiffnesses simultaneously acting on the Test Mass along 2 different soft DoFs. The advantages with respect to a single DoF test bench are a more effective identification and debug of spurious effects between the TM and the capacitive position sensor surrounding it and the possibility to test actuation crosstalk with closed feedback loop. In particular, it allows us to measure the residual disturbance along one DoF when we close the control loop on the other one.

1. Introduction
The LISA requirement for the residual acceleration noise in the free-falling frame of the test-mass $m_{TM}$ is [1]:

$$
\frac{S_{\beta}}{m_{TM}}^{1/2} \leq 3 \cdot 10^{-15} \left[ 1 + \left( \frac{f}{3\text{mHz}} \right)^2 \right] \frac{m}{s^2 \sqrt{Hz}}
$$

for $0.1\text{mHz} < f < 0.1\text{Hz}$. A drag-free operation mode is necessary, with minimal coupling between TM and spacecraft, so that the above requirements can be met.

A capacitive sensor system (GRS, Gravitational Reference Sensor) [2], is used to read out the position of the TM with respect to the spacecraft. This represents the error signal provided to the control loop that uses micro-thrusters as actuators to force the spacecraft to follow the TM.
In the case of a single-mass/single-axis control loop, the residual closed-loop TM acceleration is:

\[ a_n \approx \frac{f_{sr}}{m_{TM}} + \omega_p^2 x_n + \frac{F_{S/C}}{M\omega_{DF}^2} \]

Ground tests are required to study the residual weak forces that may couple the TM to the GRS. The challenge for these tests is to cancel gravity, in order to simulate a free fall condition along as many DoFs as possible. Up to now, very good results were obtained with a torsion pendulum, that only allows to study one single DoF [1].

### 2. The Roto-Translational Pendulum

The geometry of the roto-translational pendulum [3], [4], [5] allows us to have 2 soft DoFs. The rotations around the two fibers are indicated by the independent angles are \( \varphi \) and \( (\theta - \varphi) \) (figure 2). The \( \varphi \) rotation approximates a linear (translational) displacement \( x \) at the tip of the arm of the crossbar.

| \( \varphi \) pendulum | (\( \theta - \varphi \)) pendulum |
|------------------------|-------------------------------|
| Material               | tungsten                      |
| length                 | 90 cm                         |
| diameter               | 100 \( \mu \)m                |
| momentum of inertia    | 0.02 kgm\(^2\)               |
| frequency              | 1.5 mHz                       |
|                        | Tungsten                      |
|                        | 90 cm                         |
|                        | 25 \( \mu \)m                 |
|                        | 3.38 \( 10^{-6} \) kgm\(^2\) |
|                        | 2.4 mHz                       |

The roto-translational pendulum is hosted in an Al5083 vacuum chamber 3\( m \) high, and 1\( m \) in diameter. Two remotely controlled motors allow us to rotate the \( \varphi \) fiber around its axis, and to raise or lower its suspension point. The central \( \varphi \) fiber holds a crossbar; at the tip of one of its arms we connect the \( (\theta - \varphi) \) fiber, at the bottom of which the TM is hanging. To balance the crossbar, three more masses are rigidly fastened to the tips of the remaining crossbar arms. We minimized the quadrupole moment with an appropriate distribution of the balancing masses. The TM position is measured by capacitive sensors mounted in a cubic box (the GRS); the GRS can be remotely moved along 6 DoFs, in order to place the TM at its center with an accuracy of a few \( \mu \)m.

![Diagram](image-url)
With a scroll plus turbomolecular pump system we rapidly achieve a pressure of $10^{-5}$ mbar; after heating the vacuum chamber at about 80 °C, we obtained a pressure of about $10^{-6}$ mbar.
3. Read Out
The position read out of the TM is achieved with capacitive and optical devices. The optical system is used for calibration.

3.1. Capacitive Read Out
The capacitive sensing and feedback electronics were designed building on the experience of analogous devices previously developed for similar, single DoF applications [6], [7]. Each of two identical channels reads out a pair of capacitive sensors placed along the x axis of the GRS on opposite sides of the TM: the two pairs are placed parallel to each other, but at a different y position. The signal is modulated at about 100kHz, and then read and demodulated with a lock-in amplifier. Sum and differences of these two channels outputs provide information about translation along x axis and rotation (θ-φ) as defined in Par.2, respectively. The capacitors are also used as electrostatic actuators, to close a feedback position loop on the TM.

3.2. Optical Read Out
In addition to the capacitive readout, an optical readout scheme is also implemented, based on a commercial autocollimator (Elcomat Vario 300). The autocollimator can be mounted in two different positions, to measure either the angle φ, or the angle (θ-φ) using to two mirrors rigidly mounted on the TM and the crossbar, respectively.
4. Magnetic Noise Measurements

Fluctuations in the local magnetic field may couple to the magnetic moment of the roto-translational pendulum and act as weak forces between TM and its environment. We used three triaxial magnetic probes to measure the magnetic field and its gradient around the TM position, placing a \( \mu \)-metal cylinder 0.4 mm thick around the sensor, as a magnetic shield. We estimate the magnetic moment of the pendulum to be a few \( 10^{-9} Am^2 \) on the basis of measurements [7] on the same test mass, and in a similar setting, and with this value we compute the expected torque noise generated by magnetic field fluctuations. As it is shown in figure 11, this noise is negligible, even when no magnetic shield is present (red curve).

![Figure 10. The magnetic field sensors.](image)

![Figure 11. Torque (\( \tau \)) noise induced by the fluctuation of the magnetic field. The thermal noise limit is plotted in green color.](image)

5. Calibration and Qualification Measurements

We calibrated the displacement sensor on the bench; then we measured the readout noise with the two DoFs blocked, the TM being held in position by a shaft and the crossbar resting on a support. The sensitivity is better than 2 nm/\( \sqrt{Hz} \) down to 50 mHz, and it is adequate to reach the thermal noise limit of the two pendulum stages; at lower frequencies the noise is higher, with a consistent contribution from the residual motion of the test mass.

![Figure 12. The plot on the left shows the spectral density, expressed in displacement units (nm/\( \sqrt{Hz} \)) of the readout noise plus environmental noise. The shaft that holds the TM is not perfectly rigid, and the residual motion of the TM generates the broad peak around 0.4 Hz. The inset shows the calibration of the capacitive position sensor.](image)
6. Commissioning of the Roto-translational Pendulum

We integrated the sensor and the TM to the facility: the calibration of the capacitive readout is found consistent with the autocollimator read out of the position angle. Then we qualified the pendulum, first blocking the degree of freedom in translation, allowing for the TM to rotate around its axis inside the sensor. We measured for the rotation degree of freedom a frequency of 2.35 mHz, with the quality factor Q of about 750, at a pressure of 10^{-6} mbar. As soon as a third electronic board will be delivered, we will be able to unblock the degree of freedom in translation.

![Figure 13. PSD in angle measured for the degree of freedom in rotation. In blue, the optical autocollimator read out; in green the capacitive readout, measured with a time constant of 20s; in red the thermal noise and electronic readout noise.](image)

Figure 13 shows one of the first measurements of the angular PSD. Bringing the curves to the thermal noise level is one of the goals of the commissioning.

As we said, the capacitors are also used as electrostatic actuators, to close a feedback position loop on the TM. A Labview routine processes the position signal read from the electrostatic sensors, filters it to obtain a critical damping, and feedbacks a voltage modulated at 200 Hz to the capacitors.

![Figure 14. Closing the feedback loop on rotation: in the top panel the voltage read with the capacitive device is plotted versus time; in the bottom panel, the angle is reported.](image)
7. Next Steps

The next steps of the activity on the 2DoFs pendulum will be:

- To improve the electronic noise figure below 50mHz.
- To achieve the noise specification for each degree of freedom (basically the thermal noise of the fibers that is in terms of force about $10^{-13}$ N/√Hz at frequencies below the resonant frequency of the torsion pendulum).
- To start measurements with the 2DoFs simultaneously free and to apply a feedback control to either one or both of them.

8. References

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