The 2 Degrees of Freedom Facility in Firenze for the study of Weak Forces

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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 cross-talks of read-outs and actuators operating on different DoFs. To best represent the flight conditions, we developed in Firenze a facility with 2 soft DoFs. Using this facility we measure the forces and stiffnesses acting simultaneously along the 2 soft DoFs, and, more specifically, we will be able to debug residual couplings between the TM and the capacitive position sensor that reads the TM position, and to measure actuation cross talks with closed feedback loop. The facility is now ready, and here we report on the commissioning tests, and on the first measurements.

1. Introduction

The LISA requirement for the residual acceleration noise in the free-falling frame of the test masses M is [1]:

$$\frac{S_f^{1/2}}{M} \leq 3\cdot 10^{-15}\left[1+\left(\frac{f}{0.003Hz}\right)^2\right]\frac{m}{s^2\sqrt{Hz}}$$

for $0.1mHz < f < 0.1Hz$. A drag-free operation mode is necessary, with minimal coupling between test mass and spacecraft, so that the above requirements can be met. A capacitive sensor system (GRS, *Gravitational Reference Sensor)* [2] is used to provide the relative position input to the contol loop that is closed on micro-thrusters that force the spacecraft to follow the test-mass. In the case of a single-mass/single-axis high gain control loop, the residual closed-loop test mass acceleration [1], is (parameters are indicates in figure 1):

$$a_n \approx \frac{f_{str}}{m} + \omega_p^2\left(x_n + \frac{F_{S/C}}{M\omega_{DF}^2}\right)$$

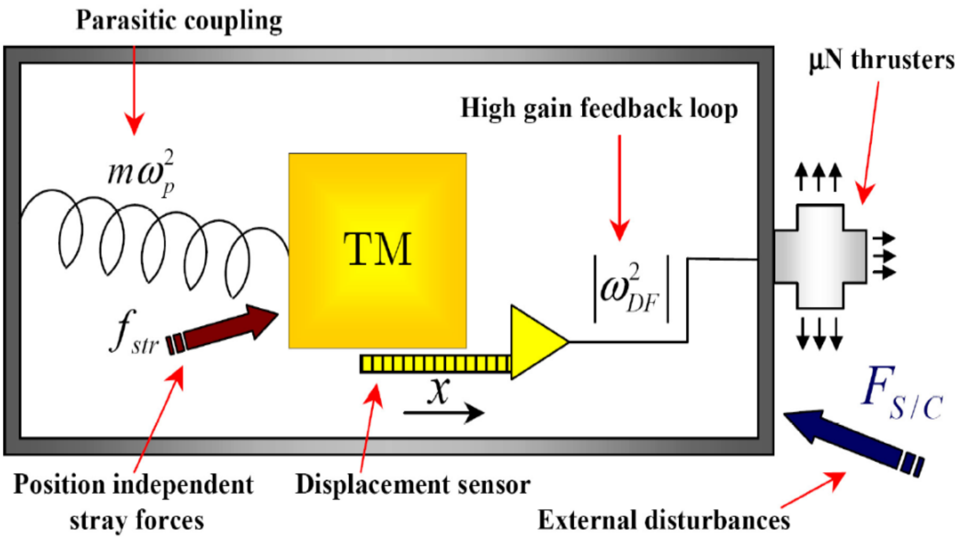

Figure 1. A sketch of the interaction between the spacecraft and the test mass.

Ground tests are required to study the residual weak forces that may couple the Test Mass 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 have been obtained with a torsion pendulum, that only allows to study one single DoF [3], [4].

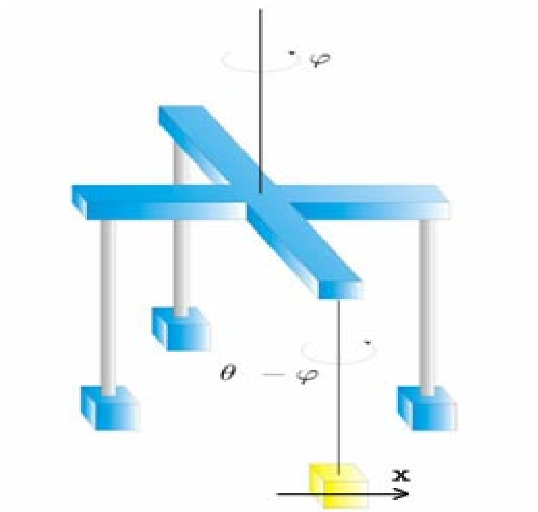

Figure 2. Schematic of the roto-translational pendulum.

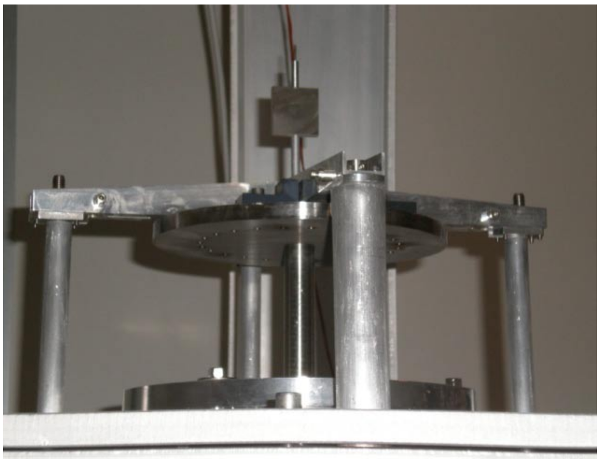

Figure 3. The crossbar.

2. The Firenze facility

Our two DoF facility (the scheme is in figure 2 and 3) will better represent the flight conditions where the test mass is sensitive to force along all 6 DoFs [5], [6]. The facility will measure the forces and stiffnesses simultaneously acting along different soft DoFs. The advantages with respect to a single DoF test bench are a more effective identification and debug of spurious effects and the possibility to test actuation cross talk 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. More details in [7], [8].

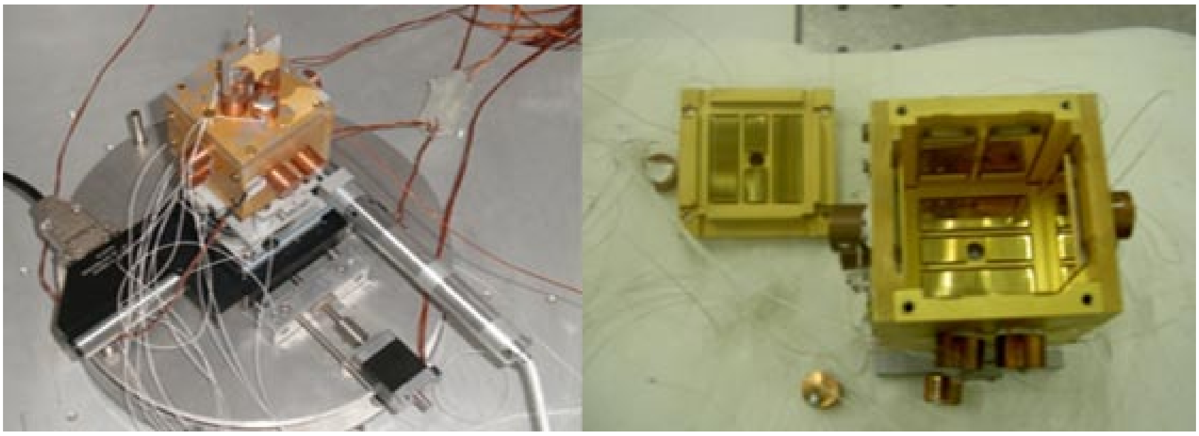

Figure 4. The capacitive sensor (GRS).

3. Sensing and actuation via capacitive coupling

The capacitive sensing and feedback electronics was designed building on the experience of analogous devices previously developed for similar, single degree of freedom applications [3]. Each of two identical channels reads out (and actuates) a pair of capacitive sensors (figure 4) placed along the x axis of the GRS on opposite sides of the Test Mass. Sum and differences of these two channels outputs provide information about translation along x axis and rotation (θ-φ) as defined in figure 2. The signals are modulated at about 100kHz (in green the injection electrodes, figure 5), and then read and demodulated with lock-in amplifiers. The capacitors are also used as electrostatic actuators, to close feedback position loops on the TM. We have recently implemented a second version of this electronics, where the actuation and sensing are separated on different boards, in a modular design. With this set up, hosted in a NIM crate, we can add readout and feedback channels as we need.

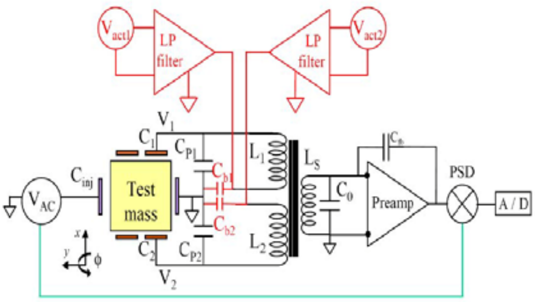

Figure 5. The capacitive sensor (GRS).

4. Closing the feedback loop on position

The output signals are filtered by the lock-in amplifiers, and then are fed to a commercial 18 bits ADC board in a PC. A Labview routine generates a feedback signal, which is converted by a DAC, which provides the input to an analog board, where is amplified, modulated at 200 Hz, and then sent to the same pair of sensing capacitors, to obtain an electrostatic damping of the oscillations, and hold the test mass in place. The frequency response of servo is generated with a PID network:

$$G(s) = G_1 \frac{1}{\omega_1 + s}\left(s^2 + \omega_0^2 + \gamma_G s\right)\left(\omega_{lockin} + s\right)\frac{1}{s^2 + \omega_2^2 + \gamma_2 s}$$

where G_1 is the gain of the loop, ω_1 is the cut frequency of the filter, ω_0, γ_G are the resonant frequency and the damping coefficient of the rotational pendulum, ω_{lockin} is the cut frequency of the output of the lockin and ω_2, γ_2 are the resonant frequency and the damping coefficient of the a further filter to stop noise from the high frequency (see figure 6 for the scheme).

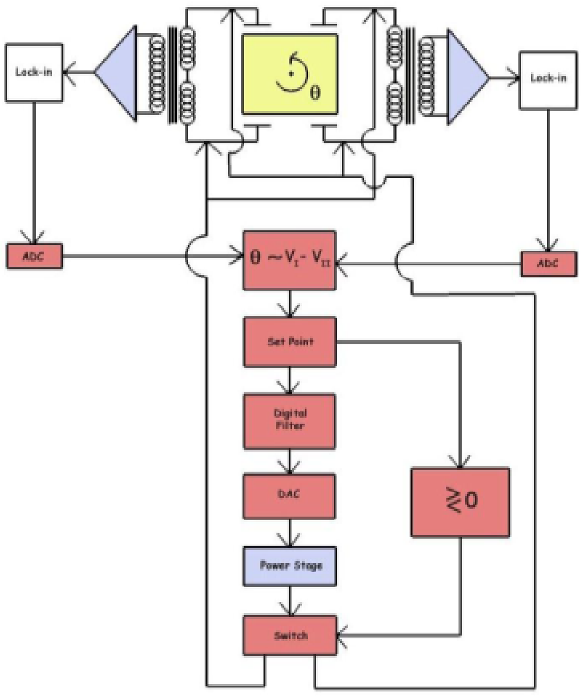

Figure 6. The block diagram of the feedback loop.

In the figures 7,8,9 it are shown the outcome of some of the first tests, made with the translational degree of freedom blocked.

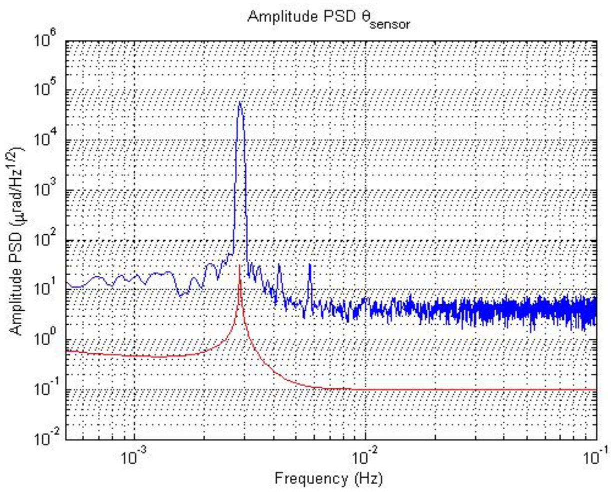

Figure 7. Measurement of the resonance frequency of the (θ-φ) pendulum. The red line is the sum of the thermal noise of the pendulum and the capacitive read-out noise.

We are presently engaged in the task of defining and implementing an algorithm that will allow us to acquire control of both Dofs simultaneously. The read out noise limited sensitivity is better than 2 $nm/\sqrt{Hz}$ down to 50 *mHz* [7]. It translates to a sensitivity in force of 10^{-13} $N/\sqrt{Hz}$, for the translational DoF, and of 2.5×10^{-14} $N/\sqrt{Hz}$, for the rotational DoF, 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.

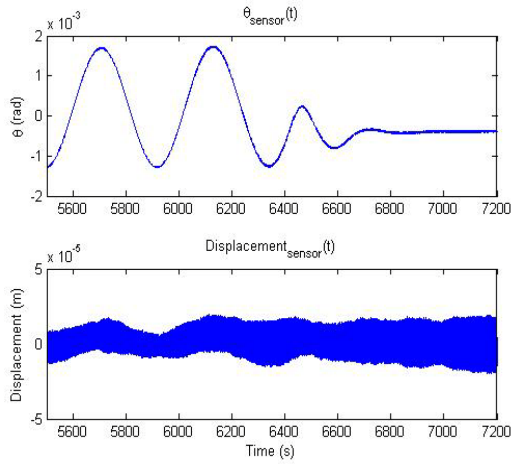

Figure 8. Closing the loop we damp only the rotation but not the translation (pendulum motion).

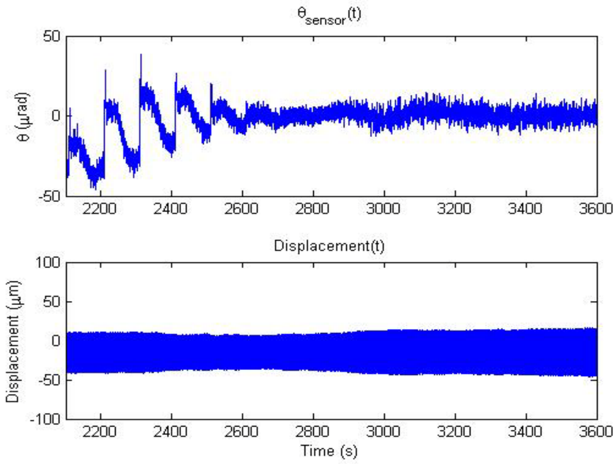

Figure 9. The feedback implemented after centering the capacitive sensor using the motorized rotation stage.

5. Optical position sensing: autocollimator and optical lever

A great flexibility can be obtained using second position readout, independent from the hardware through which the feedback is applied. Cross correlation of optical and electrostatic readout have proven effective in reducing the readout noise [4]. In addition to the capacitive readout, two optical readout schemes will also be implemented, one for each degree of freedom.

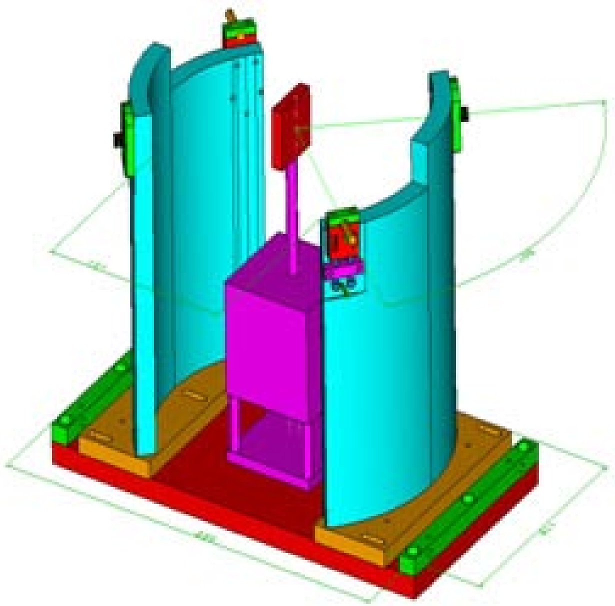

Figure 10. 3D scheme of the optical lever read-out.

The first is based on a commercial autocollimator (Elcomat Vario 300). It will read the rotation of the mirror attached to the crossbar, and it will be used to measure the angle φ, with a sensitivity of about 3×10^{-8} rad/Hz$^{1/2}$ [7] A second optical readout will soon be implemented on the facility (figure 10), and it will be used to measure rotation and displacement of the mirror attached to the TM. It will consist of two channels, that will allow to measure the displacement and the rotation (θ-φ) of the TM [9].

6. Conclusion

We have tested with satisfaction the capabilities of our two degrees of freedom facility, with one degree of freedom blocked. The next steps will be: to substitute the present TM/capacitive sensor system with a TM and a capacitive sensor more closely similar to the flight model, which will also allow an easier management of the translational degree of freedom; then, to unblock the second degree of freedom and test the performances of the entire facility; and, finally, to substitute the electronics with boards similar to the flight electronics. With that, we will have a test bench that will simulate free fall on ground, at least along two DoF's.

7. Reference

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