PETER: A DOUBLE TORSION PENDULUM TO TEST QUASI FREE-FALL ON TWO DEGREES OF FREEDOM

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Torsion pendulums are the best approximation, in the laboratory, to a body in free fall: the extremely low restoring force exerted by the torsion fiber approaches the absence of interaction with the surrounding, but only on a single degree of freedom (DOF), namely the rotation around the fiber. We present a peculiar pendulum where we achieved, by cascading two torsion fibers, almost-free motion on two DOFs: rotation around a vertical axis and translation along one axis. The apparatus was developed to serve as a test facility for LISA Pathfinder(LPF) pre-flight investigations of cross talk between different degrees of freedom, and is presently being upgraded to improve performances and reduce coupling of displacement noise to torsional degrees of freedom. We shall describe the instrument, review the cross-talk measurements performed on it for the electrostatic actuators of LPF and discuss how new experiments can benefit of the peculiarity of two (and potentially more) soft DOFs

1 Introduction

Thanks to the ability to approach free fall condition in laboratory down to a few mHz, ground testing with torsion pendulums played a crucial role in the development of the Gravitational Reference Sensor (GRS) of the LPF mission [1]. Single stage pendulum facilities developed at University of Trento, permitted to characterize the GRS for stray torque or force acting on the suspended TM [2,3]. This was achieved by using single mass and 4 mass torsion pendulums respectively, as illustrated schematically in figure 1. In this paper, we report on a two stage torsion pendulum, named PETER [a] that allows approaching free-fall in two DOFs, permitting simultaneous measurement of force and torque acting on the TM. A sketch of the two-fold pendulum is also reported in figure 1. This pendulum was designed [4] as a facility for, pre-flight ground testing of the LISA-Pathfinder GRS. A detailed description of the facility and measurement technique can be found in references [5,6,7,8].

[a] from Italian PEndolo Traslazionale E Rotazionale, namely Rotational and Translational Pendulum

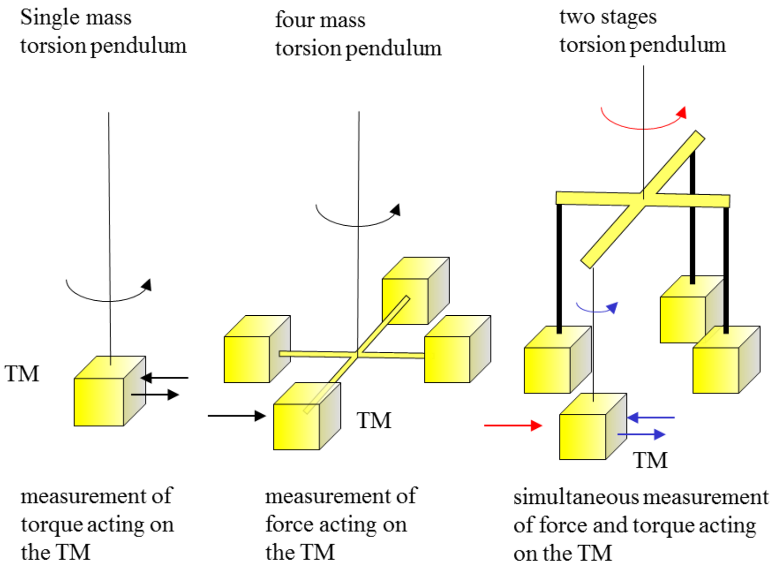

Figure 1 – single mass (left), four mass (center) and two-fold (right) pendulums

2 GRS cross-talk measurement

In 2015, we performed a campaign of six runs devoted to the measurement of actuation Cross-Talks (CT) of the Engineering Model of the LPF GRS. In table 1, we summarize the relevant information for the various measurement runs; a detailed description of the measurement technique can be found in [5,6,7,8].

Table 1: Relevant information for the six measurement runs. Run 3b was performed in constant stiffness conditions.

Run number	Run start time	Averaging time per step (hours)	Number of steps	Step size (μm)	Actuation ampl. (V^2)
Force to Torque Cross Talk (actuation force at 14 mHz)					
1a	Jun 9, 2015	3	5x5	100	50
2a	Jun 19, 2015	1.25	24 (spiral)	100	20
3a	Jun 26, 2015	2	25 (spiral)	100	20
Torque to Force Cross Talk (actuation torque at 18 mHz)					
1b	May 25, 2015	3	8	150	20
2b	May 29, 2015	3	5x5	100	20
3b	Nov 24, 2015	2	8 (spiral)	100	20

In figure 2 we report a force to torque CT measurement (run 3a) compared with an analytical model (see [8,9] and references therein for details). We also show the residuals (measured values minus model predictions) vs. x displacement. The general agreement is good with a residual small discrepancy, well represented by a linear trend along x. The results of the other force to torque CT measurements (run a1 and a2), are quite similar; the maximum difference of the three runs is below 0.05 % in CT In figure 3 we report a torque to force CT measurement (run 2b) compared wit an analytical model. We also show the residuals (measured values minus model predictions) vs. x displacement. In this case, the agreement to the model is not as good and we measure a CT much larger than expected (up to 4 %), still well represented by a linear dependence on the x coordinate. Nevertheless, in the central part of the measurement range, that is of interest for the scientific operation of LISA-Pathfinder, the measured CT is still very

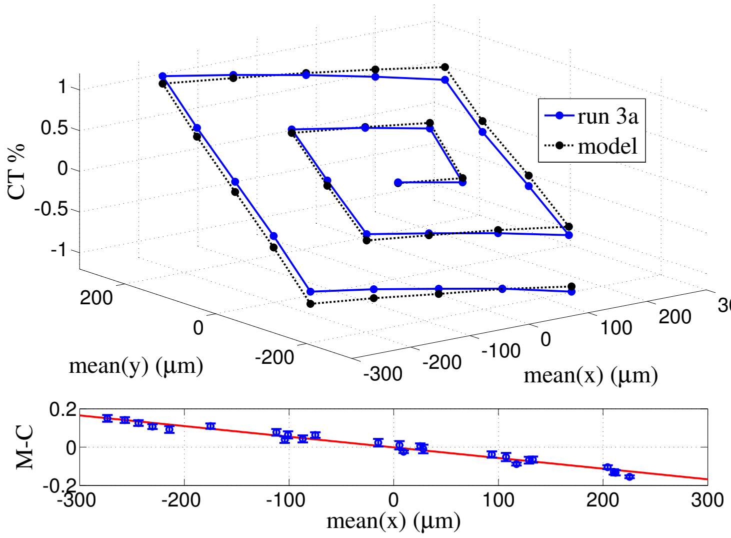

Figure 2 – Force to torque CT measurement for the run 3a, compared to the analytical model. In the lower part of the figure the M-C residuals (Measured-Computed) are shown versus the x coordinate.

small (below 0.8% in the central 50 μm and less than 0.2 % at the GRS center). Also in this case the measurement are quite repeatable and the maximum difference from run to run (run b1 and b3), stays within the experimental error.

Summarizing, we performed several CT measurement runs. In all the cases, the CT measured at the GRS electric center was always small enough to be compliant with the LPF requirements and didn't appear problematic for the on-flight GRS operation, as was then verified by the excellent performance of the LPF mission [1]

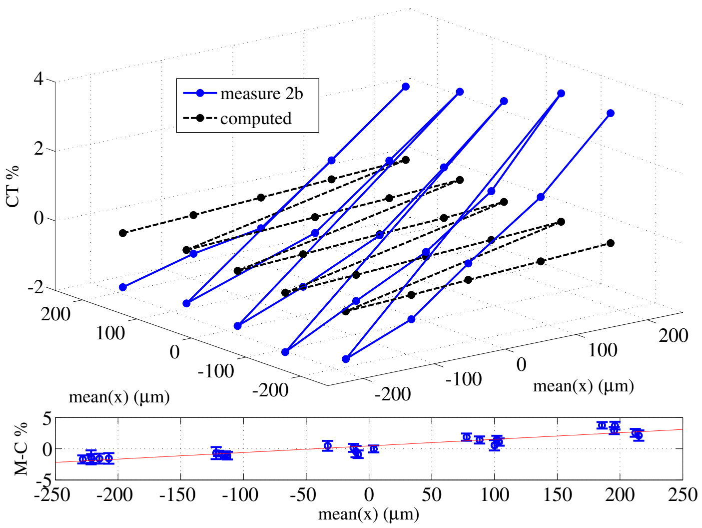

Figure 3 – Torque to force CT measurement for the run 2b, compared to the analytical model. In the lower part of the figure the M-C residuals (Measured-Computed) are shown versus the x coordinate.

3 Possible upgrades and applications

Aside to the ground-testing of the flight hardware of LISA or other drag-free space mission, a double torsion pendulum could find potential application in other field of fundamental or applied physics. As an example, we consider the measurement of the "lateral" Casimir Effect[10,11]. In this case, the usage of corrugated surfaces, generates a transverse Casimir force in addition to the "usual" Casimir pressure. From an experimental point of view, one of the main difficulties is to avoid that the transverse force is contaminated by a Cross-Talk of the, much larger, normal force. The simultaneous measurement of both normal and transverse Casimir force should simplify the analysis of the results, and permit to distinguish the different components.

Another point to mention is the possibility to extend the free fall condition to more than two DOFs (in principle, up to 6). The "easy" part is to extend to a second displacement in the horizontal plane; this can be achieved by cascading a third off-axis torsion pendulum hanging a second cross-bar to the first one. Things become more difficult if we consider the DOFs where the restoring force is dominated by the local gravitational acceleration. For what concerns the rotations around the two horizontal axis, if we move the TM attaching point close to the Center of Mass (CM), the restoring torque, for rotation around CM approaches zero and the resonance goes to low frequency. In real life, there are severe limitations due to mechanical tolerances, TM inhomogeneity, and lateral accuracy in attaching the suspending wire. As the last, perhaps more difficult, DOF, we consider the vertical direction, where we directly compete with g. In this case, we should suspend the attaching point of the first fiber to one end of a beam balance with a flexure joint. Such a setup has been realized as a tilt-meter for the LIGO interferometers[12], permitting to reach a resonance frequency as low as 10.8 mHz.

In conclusion, we think that a laboratory free-fall condition with more than two DOFs is on the reach. Several applications could benefit from the availability of such facility.

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References

1. M. Armano *et al*, *Phys. Rev. Lett.* **116**, 231101 (2016).
2. L. Carbone *et al*, *Phys. Rev. Lett.* **91**, 151101 (2003)
3. F. Antonucci *et al*, *Class. Quant. Grav.* **29**, 124014 (2012).
4. R. Stanga *et al*, *J. Phys. Conf. Ser.* **154**, 012032 (2009).
5. F. De Marchi *et al*, *Phys. Rev.* D **87**, 122006 (2013).
6. M. Bassan *et al*, *Phys. Rev. Lett.* **116**, 051104 (2016).
7. M. Bassan *et al*, *Measurement, with the PETER facility, of force to torque cross-talk in actuation of the LISA-Pathfinder GRS*, LFGN-NOTE-1-2015, internal note of the Laboratory of Gravitational Physics, Napoli (2015).
8. M. Bassan *et al*, *Measurement, with the PETER facility, of torque to force cross-talk in actuation of the LISA-Pathfinder GRS*, LFGN-NOTE 1-2016. internal note of the Laboratory of Gravitational Physics, Napoli (2016).
9. M. Bassan *et al*, *Actuation cross-talks in free-falling systems: torsion pendulum results for the LISA-Pathfinder gravitational reference sensor*, *Astrop. Phys.* (2017) submitted.
10. F. Chen *et al*, *Phys. Rev. Lett.* **88**, 101801 (2002).
11. T. Emig *et al*, *Phys. Rev.A* **67**, 02211 (2013).
12. Venkateswara *et al*, *Rev.Sci.Instrum.* **85**, 01500 (2014)