DYNAMIC ADHESION MEASUREMENT FOR THE VERIFICATION OF THE GRABBING POSITIONING AND RELEASE MECHANISM FOR THE LISA PATHFINDER TEST MASS RELEASE

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ABSTRACT

A critical phase for both the joint ESA-NASA scientific mission LISA and its technology demonstrator LISA Pathfinder has been identified in the release to free floating conditions of the 2kg gold-coated Test Mass (TM) on behalf of the Grabbing Positioning and Release Mechanism (GPRM), developed by Thales Alenia Space and RUAG. The main criticality of such a phase consists in the limited allowable velocity of the test mass after detachment from the GPRM. In this paper we deal with the on-ground testing activity of such a phase carried out at the Dept. of Mechanical and Structural Engineering of the University of Trento, where we have developed a facility for the measurement of the impulse exerted by the rupture of the adhesive bonds between representative surfaces of the TM and the release-dedicated subsystem of the GPRM.

1. INTRODUCTION

Adhesion phenomena, even in a space environment, have been extensively investigated in the literature ([1][2]), but their role on the release of objects to free-floating conditions in space applications has not been thoroughly studied yet. The in-orbit precise release of a body implies the separation of its contacting surfaces from the engaging surfaces that belong to some kind of caging device. As this separation involves the rupture of the unavoidable adhesive forces, an impulse is developed on the object at any contact point. In absence of constraining non-contact forces that balance the net impulse, the separation of the mating surfaces must rely on the body inertia and result in a transfer of momentum to the released object. The critical aspect of this issue is twofold. First, due to the poor repeatability of adhesion phenomena, it is not possible to rely on the mutual balancing of the developed impulses, even with a symmetrical configuration. Second, in the space environment, the rupture of the interaction forces between contacting bodies is promoted neither by the gravity field, nor by surface contaminants caused by exposure to the atmosphere, nor by seismic and air-propagated acoustic noise.

A meaningful example of these issues is given by the ESA-NASA joint scientific space mission LISA (Laser Interferometer Space Antenna) and its precursor LISA Pathfinder. Aim of LISA is the first in-flight revealing of gravitational waves, which will be detected by means of laser interferometers arms formed among three orbiting satellites. The gravitational waves sensing elements, constituting the end-mirrors of the interferometer arms, will be 2kg Au/Pt cubic masses located within the satellites. During the launch, the test masses (TM) need to be firmly secured to their housings in order to avoid shaking and thus damage. During the experiment, the test masses need to be released in free flight. The release of the LISA Pathfinder test masses is performed by the Grabbing Positioning and Release Mechanism (GPRM), that is being developed by Thales Alenia Space and RUAG.

Some boundary conditions make the operation of the release-dedicated mechanism of the GPRM critical. First, the TM and any facing surface must be gold coated, in order to limit stray electric fields that would convert into force noise on the TM itself. Second, a limited (μN order) force and torque authority on the floating TM is available supplied by a set of surrounding electrodes that constitute a capacitive actuation system. It has been experimented [1] that gold-coated surfaces easily develop a mN-order adhesion force even at low preloads, that is at least three order of magnitude larger than the force authority. As a consequence, an impulsive detachment of the release finger from the TM on behalf of the GPRM resulted the only viable solution and has been analyzed in [3]. The limits in the TM control force and the available gaps with the electrodes convert in a requirement on its residual velocity after release that must be less than 5 μm/s (10^{-5} Ns linear momentum). Due to the criticality of the release and capture phase of

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the TM for the entire mission, a ground based verification has been requested.
Dynamic adhesion measurements aimed at determining the momentum transfer followed by the separation between adhering bodies had not been performed yet. An experiment has been designed and its conceptual model has been proposed by the authors in [4], indicating that a basic requirement is to prevent adhesion rupture induced by force/torque components acting along constrained degrees of freedom of the experimental device; the measuring apparatus and its performances in terms of measurement resolution have been illustrated in [5], the preliminary results of momentum transfer measurement between aluminum mock-ups have been presented in [6]. The present paper presents for the first time measurements of momentum transfer between representative surfaces of the LISA Pathfinder TM and the GPRM.

2. ON-GROUND TESTING OF THE RELEASE PHASE

2.1 Dynamic adhesion measurement technique

The on-ground testing approach of the GPRM/TM release phase is based on the measurement of the impulse developed by the rupture of adhesive bonds between replicas of the TM and release finger mating surfaces in representative conditions of the in-flight ones. The GPRM release performance is considered compliant with the requirement if the impulse results lower than 10^{-5} Ns.
Precise measurement of impulse performed by other authors [7, 8] resulted critical, mainly for two reasons. Firstly, the force impulse needs to be entirely converted into momentum; therefore, any other force acting in the same direction on the body subjected to the impulse must be minimized. Secondly, the momentum must be identified by the measurement of the resulting motion of the body that is affected by noise sources and by the unavoidable constraining forces. The conversion of impulse into momentum may be guaranteed by a suspension system that minimizes the risk of any impulsive constraining force in the direction of the impulse to be measured. Suspension systems based on simple pendulum, linear rail and torsion pendulum [8, 9] have been adopted to provide a weakly constrained axis. The presence of a single weakly constrained degree of freedom does not limit the measurement, as long as the impulsive force is a non-contact force and it is reasonably aligned with the "soft" axis. On the contrary, the impulsive force due to adhesion rupture is affected by the complete three-axial stress status at the contact patch that depends on how both contacting bodies are constrained to ground. This means that the body subjected to the adhesive impulse needs to be weakly constrained not only in the direction along which the finger is retracted, but also along the orthogonal directions.
Neglecting, for the moment, the stiff constraint along the vertical direction, the simple pendulum model for the inertial isolation system has been chosen to investigate the possible performance of the transferred momentum measurement experiment. As long as the pendulum length is compatible with the typical height of a laboratory ceiling (i.e. meter scale), the preferred practical implementation is the simple pendulum characterized by easily determinable dynamic properties (quality factor and resonant frequency) and still providing good isolation from gravity and micro-seismic noise. The basic concept of the measuring apparatus, illustrated in Fig. 1, is to suspend both the test mass and the release finger from two pendulums. A position sensor detects the weakly damped oscillation of the test mass mock-up due to the momentum transferred upon pulling the contacting finger mock-up away.

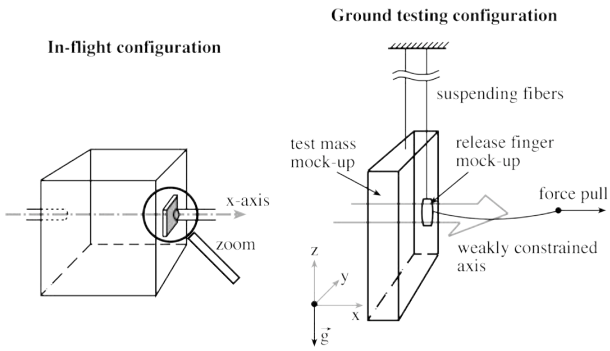

Figure 1. The concept of the release phase ground testing setup: two pendulums with nominally equal lengths represent the TM and the finger respectively. A position sensor detects the swing motion of the TM due to the momentum transferred upon pulling the finger away from the contact

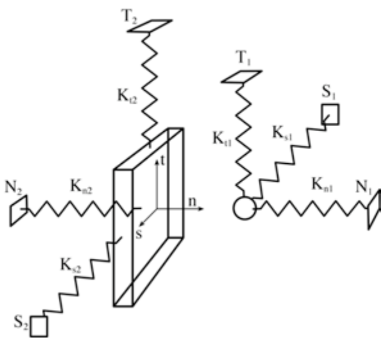

Figure 2. Schematic representation of the constraining stiffness of the two initially contacting bodies in the ground-based experimental configuration. The suffixes 1 and 2 refer to the finger and TM mock-up respectively

In the configuration shown in Fig. 1, however, the stress status on the contact patch may be in principle far different in the ground experiment from the in-flight conditions. The in-flight release takes place with an unconstrained test mass, and for equilibrium shear stresses at the contact patch are not allowed along any of the directions laying on the common contact plane. In the ground experiment (see Fig. 2), both the test mass mock-up and the finger mock-up need to be suspended with some constraining stiffness to ground, named K_n, K_t and K_s. There are two main reasons for keeping the constraining stiffness to the lowest possible value, that are addressed in the following sub-sections.

2.1.1 The role of the gravity force

The separation of the contacting bodies involves the fracture of the bonding junction. Since all stress components acting on the junction contribute to its fracture, the presence of shear stress in the ground-based experiment may help the rupture of adhesion and leads to an underestimation of the impulse occurred at the separation with respect to the in-flight conditions. The risk of a gravity-aided adhesion rupture may be firstly limited by adopting a very light finger mock-up that is represented by a millimetre-order diameter lenticular mock-up. Secondly, the tension on the finger mock-up suspending wire is measured by a load cell in order to monitor any variation of the vertical force with respect to the weight during the approach to the test mass mock-up.

2.1.2 Micro-seismic related kinetic energy

The adhered finger constitutes a body bound in a force potential well. One condition in order the momentum transfer not to be obscured by other phenomena related to the ground environment is that the force noise acting on the TM and the finger (e.g., seismic noise) does not induce on the finger a kinetic energy relative to the TM sufficient to overcome the binding energy. Consequently, the suspension system shall provide sufficient isolation from noise sources acting in the laboratory environment.

2.2 Signal optimal filtering technique

The force impulse due to the adhesion rupture is measured by means of the following free oscillations of the TM mock-up pendulum. Thanks to the accurate alignment of the two contacting pendulums and the intrinsic robustness of the experiment concept, the force impulse is mainly converted into a swing oscillation of the TM mock-up. The measurement accuracy is therefore limited by the superimposed noise to the swing-mode signal, mainly due to the ground micro-seismic activity and the readout system.

Different techniques have been used in the literature to extract the applied impulse from the measured free oscillation of the suspended system [8]. In this paper, we adopted the standard Wiener-Kolmogorov Filter (WKF) theory of optimal estimation [10] to assess the momentum transferred by an impulsive force to a harmonic oscillator. We assume that a harmonic oscillator of mass m, resonant angular frequency ω_0 and quality factor Q, is subject to a force of total impulse P_0. The readout of the position x of the oscillator is affected by a stationary and Gaussian noise with PSD $S_x(\omega)$. The momentum transferred from the force to the mass is measured from the motion of the oscillator as detected by the readout, which is given by:

$$x(t) = As(t) + n(t) \tag{1}$$

where $s(t)$ is the response signal of the system to a unit impulse (known), A is the signal amplitude, function of the unknown impulse, and $n(t)$ is the noise. We now look for an optimal estimator of the signal amplitude from a linear combination of the data $x(t)$:

$$\hat{A}(T) = \int_0^T h(t')x(T-t')\mathrm{d}t' \tag{2}$$

where the 'filter'' function $h(t)$ has to be chosen such that is an unbiased estimator and its variance is minimal. It can be demonstrated that a set of measurements in presence of the superimposed noise $S_x(\omega)$ is characterized by a standard deviation of the estimated value of the transferred momentum that is given by:

$$\sigma_{P_0} = \left[\frac{1}{2\pi m^2} \int_{-\infty}^{\infty} \frac{\dfrac{1}{(\omega_0^2-\omega^2)^2+\omega^2\omega_0^2/Q^2}}{S_x(\omega)} \mathrm{d}\omega \right]^{-\frac{1}{2}} \tag{3}$$

Notably, the measurement precision of the transferred momentum increases with decreasing TM mass, suggesting the employment of a light mock-up of the TM itself in the release experiment.

3. THE TRANSFERRED MOMENTUM MEASUREMENT FACILITY

The transferred momentum measurement facility (TMMF), shown in Fig. 3, consists of a vacuum chamber in which the two mock-ups are suspended by means of 1-m long pendulums, and in an optical bench where the optical readout of the test-mass mock-up displacement, pitch and yaw is implemented. The facility can be schematically subdivided in 4 subsystems:

- *Vacuum system*. It is devoted to guarantee the high vacuum level needed for the experiment
- *Suspension and positioning stage*. It is aimed at suspending TM and finger mock-ups as well as at positioning the TM with respect to the finger mock-up (along x, y, z and ϕ-axes, where ϕ-rotation is around z-axis). In addition, this subsystem is devoted to monitor the force acting along the suspension fibre of the release finger by means of a load cell.
- *Position readout system*. This subsystem is devoted

to measure the position and attitude of the TM mockup. The TM position along the x-direction is monitored by a laser interferometer, rigidly mounted on an optical window fixed to the vacuum chamber, and detecting the TM through an optical viewport. The TM attitude (pitch and yaw) is monitored by an optical leverage, realized with a laser beam reflected by the TM rear (-*x*) surface and hitting a Position Sensing Device.

- *Actuation system*. This subsystem is devoted to the actuation of the release finger along the direction monitored by the laser interferometer (*x*-axis). Moreover, the position of the actuation point can be varied by means of a positioning stage (along *z*-axis).

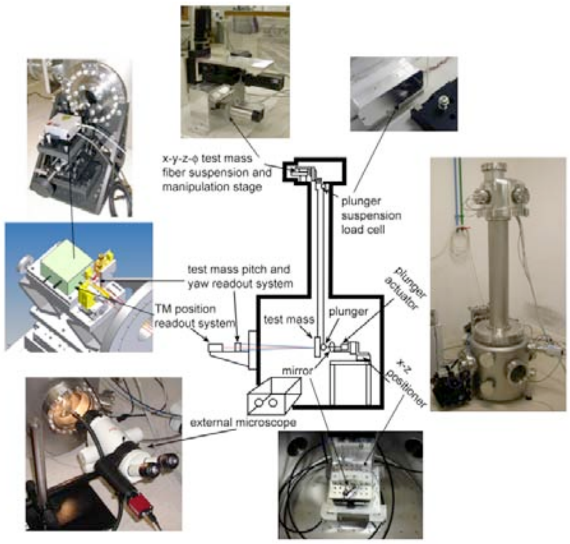

Figure 3. Layout of the transferred momentum measurement facility

The experiment fulfils the basic requirements to guarantee the smallest risk of shear-aided detachment between the two bodies, by means of a very light finger and the monitoring of the vertical constraining force exerted by its suspending fibre. This set-up also minimizes the effect of ground micro-seismic motion on the suspended system that may help adhesion rupture. Although any adhesive phenomenon arising from the preloading force between TM and finger may be progressively reduced by iteration of the detachment and lighter re-attachment of the mating surfaces, there is an adhesion threshold due to conservative interactions (Van Der Waals, electrostatic) under which the developed impulse upon rupture can not be reduced. Aim of the designed setup is then to characterize the adhesive impulse in the case of a virtually zero-preload, in order to set a lower limit of the possible momentum transfer. Thus, the TM needs also to be lightened in its mock-up version in order to reduce the restoring force per unit displacement. This reduces the risk of undesired pre-load between the two bodies and lets the TM develop a more detectable oscillation after the impulse action.

3.1 The accuracy of the measurement system

After a commissioning phase, in which the measurement performance in terms of accuracy has been characterized, the current setup of the TMMF is intended to characterize the actual imparted linear momentum to the TM. Representative gold-coated mock-ups have been used. Tight tolerances have been set on their machining, in order to achieve a good alignment of the centres of mass and vertical attitude of the contacting surface. The mock-ups have been ultrasound cleaned in isopropilic alcohol. The performance of the finger actuation stage in terms of maximum acceleration is significantly lower than that foreseen for the flight model. Fig. 4 shows in detail the mock-ups of the Test Mass and the finger. The TM is a prismatic 22×22×4 mm^3 Ti specimen suspended from a 1.14 m long Al wire with 0.125 mm diameter. The finger is a 2mm diameter Ti lenticular specimen suspended on a 1.14 m long W wire with 0.025 mm diameter and retracted by a 30 mm long W wire with 0.025 mm diameter. The finger mock-up surface radius of curvature at the contact reproduces the actual curvature of the GPRM release finger. The finger retraction fibre is actuated by a linear stage along the *x*-direction. Both contacting surfaces are gold-coated like the actual TM and release finger ones.

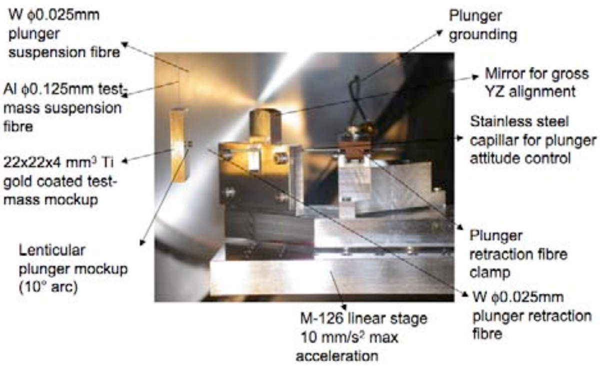

Figure 4. TM and finger mock-ups used in the experimental setup

The position readout noise and the micro seismic horizontal displacement constitute the major sources of physical disturbance superimposed on the TM free oscillations, therefore an experimental campaign has been carried out in order to characterize the noise level of the impulse measurement. To this purpose, the readout noise of the laser interferometer has been evaluated by measuring the position with respect to the measuring device of a mirror rigidly mounted inside the vacuum chamber. The spectral density of the position readout noise, plotted in Fig. 5, has been obtained by signal detrending, averaging 10 time windows, and by applying the Hemming windowing

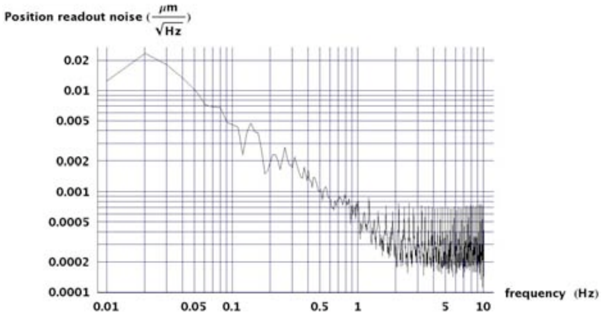

Figure 5. Spectral density of the measurement noise of the laser interferometer used to monitor the TM position

It can be noted that the spectral density is equal to about 10^{-9} m/√Hz around the 0.465Hz resonant frequency of the pendulum, where most of its effect is concentrated.

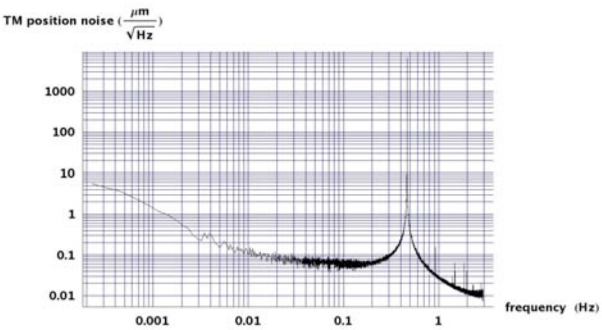

Figure 6. Spectral density of the TM position noise

The laser interferometer has then been used to measure the TM free oscillation over a long time scale (10 h). The spectral density of the position readout, shown in Fig. 6, has been obtained by averaging 10 time windows and by applying the Hemming windowing. In order to determine the spectral density of the seismic acceleration noise, the PSD of the position readout has been divided by the squared module of the transfer function between horizontal seismic acceleration and position readout of a harmonic oscillator with resonant frequency ω_0 and quality factor Q. These constants have been measured by means of a long acquisition of free oscillations subsequent to an initial excitation.

The spectral density of the seismic acceleration noise, plotted in Fig. 7, shows a constant value of about 10^{-6} m s^{-2}/√Hz around the resonance frequency. This noise level results dominant around the resonance frequency, where the impulse information is available. Therefore, as a first cut to the problem, the seismic noise model has been kept as simple as possible, in order to have a total noise at the readout signal whose power spectral density may be described by functions that still allow for analytical manipulation in the optimal filtering technique

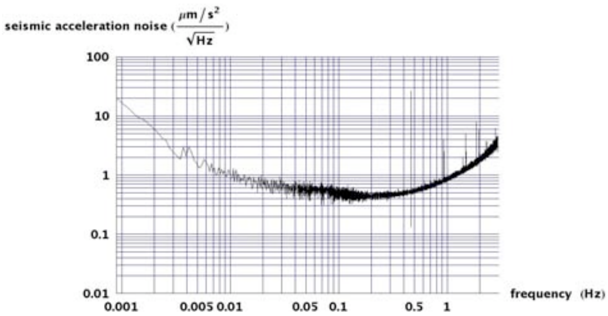

Figure 7 . Spectral density of the seismic acceleration noise

Accordingly, the horizontal displacement noise PSD has been assumed constant in acceleration and equal to 10^{-12} m^2s^{-4}/Hz, while the readout noise PSD has been assumed constant and equal to 10^{-18} m^2/Hz. By substituting in Eq. 3 the oscillator parameters and the total noise spectral density, the standard deviation σ_{Po} results $2\cdot10^{-9}$ Ns, therefore 4 orders of magnitude lower than the maximum allowed LISA TM momentum.

3.2 Theoretical model for the transferred momentum

The adhesive interactions that bind the TM and the release finger may be grouped in two categories: conservative and non-conservative.

Conservative forces are mainly due to Van Der Waals and electrostatic interactions, and may be described by an overall energy function U of the relative distance between the surfaces. A mathematical model of the TM release dynamics in presence of conservative adhesion forces has been proposed in [4], and the transferred momentum P_{cons} to the TM may be expressed as:

$$P_{cons} = \frac{\Delta U}{2\sqrt{r_0}\sqrt{a}} \tag{4}$$

where ΔU is the depth of the binding energy well, r_0 a reference range of action of the conservative forces and a is the acceleration of retraction of the finger.

Non-conservative forces are expected to be dominated by the cold welding between the gold-coated surfaces. It has been demonstrated [1] that cold weldings arise even at light preload between the surfaces and that this quantity determines the pull-off force. If we assume that the cold welding is broken by the inertia force in the incipient motion phase during which the acceleration reaches its regime value crossing the rupture threshold, the transferred momentum may be expressed as:

$$P_{diss} = \frac{constant\left(preload\right)}{m\,jerk} \tag{5}$$

where m is the TM mass, jerk is the mean acceleration derivative until the regime is reached and the numerator is a function of the preload.

In an experimental set-up where the transferred momentum is explored varying the acceleration of retraction of the finger mock-up, the overall transferred momentum is given by the sum of the contributions in Eqs.4 and 5. Being ΔU, r_0, m, *jerk* and the preload kept constant, the resulting transferred momentum is:

$$P_0 = \frac{C_1}{\sqrt{a}} + C_2 \quad (6)$$

The current experimental set-up aims at characterizing the contribution of the conservative interactions, therefore is designed to apply very low preloads between the surfaces (μN order) and impose low accelerations of retraction. However, a dissipative contribution may not be excluded, therefore the complete Eq.6 will be adopted to fit the experimental results.

3.3 Experimental procedures

The finger mock-up is initially brought near the TM until the TM oscillation (due to seismic noise) is affected by the fluctuating contact with the finger. Then, the finger is further actuated towards the TM by progressive increments of the position of the actuation stage (about 0.5 μm per each step) until a permanent contact between the finger and the TM is achieved. This can be deduced from the change in the frequency of TM oscillation. In fact, the TM pendulum (Fig. 2) is affected by the additional stiffness of the finger actuation fibre, once in contact. Before the TM-finger contact, the TM can be modelled as a harmonic oscillator with stiffness equal to the gravitational spring (K_{n2} and K_{s2}), whereas during the TM-finger contact the system can be considered as a harmonic oscillator with mass equal to the sum of those of the TM and the finger and stiffness equal to that of the gravitational spring plus the stiffness of the retraction fiber. The additional stiffness K_{n1} is estimated through the change in the resonant frequency of the oscillator, shown by the new resonance (around 2Hz) in the spectral density of the TM oscillation signal. The final position of the finger before retraction determines the initial preload of the release experiment. The position x_0 can be determined from the deviation of the initial TM position from the mean point of the TM oscillations after separation.

By limiting the advancement of the finger to the minimum required for the achievement of a stable contact, the preload between the surfaces is kept low. With a 10^{-2} kg mass, 1 m long pendulum and 10 μm of advancement, the preloading force results:

$$K_{n2} x_0 = \frac{mg}{L} x_0 \approx 10^{-6} N \quad (7)$$

Once the contact is detected, the finger retraction is postponed until the noise in TM position and attitude decreases below a conventional level, which has been set to ±0.5 μm and ±20 μrad, respectively. This conventional noise threshold before the TM release has been set in order to have comparable initial conditions among the several release experiments. Finally, the finger is quickly retracted about 300 μm from the TM. Different finger accelerations have been considered. During the first 10 s preceding and following the release, the TM position and attitude as well as the load cell signal are acquired. Typical examples thereof are plotted in Figs. 8 and 9.

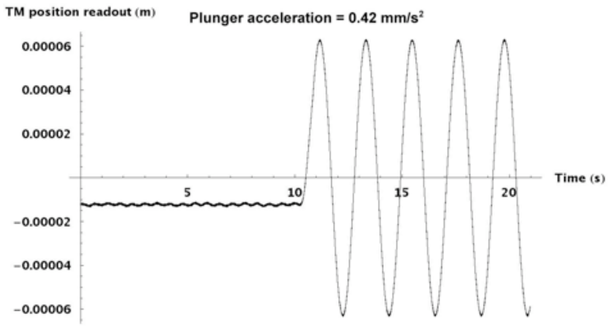

Figure 8. TM position readout before and after the finger retraction. The release instant is equal to about 10 s.

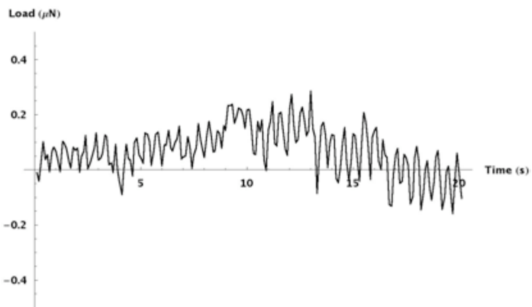

Figure 9. Variation of the signal acquired by the load cell holding the finger suspension fibre.

The application of the filter function to the readout data, detracted of the contribution of the initial position x_0, gives the estimation of the imparted impulse. Finally, no appreciable load was measured along the finger suspension fibre during the retraction. However, the exact release instant t_0 is unknown. This must be inferred from the hypothesis that t_0 corresponds to the instant in which the momentum transfer is maximum. In order to do this, the filtering function is applied to the signal by setting the reference instant (in which the impulse is assumed to be applied) in different sampled points around the nominal t_0.

Fig. 10 displays the dependence of the estimated impulse on the release instant t_0. It can be noted that the maximum value of the estimated TM linear momentum is achieved some tenths of second after the nominal release instant. This value will be considered in the following as the linear momentum transferred to the TM owing to the adhesion forces acting during the finger retraction.

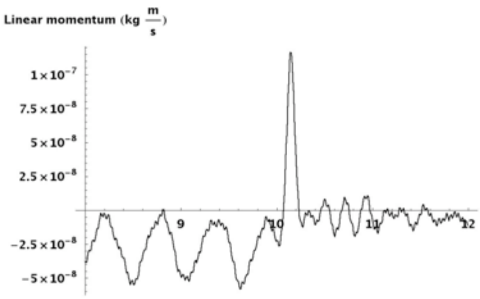

Figure 10. Variation of the estimated linear momentum with the postulated release instant.

3.4 Experimental results

It has been experimented [6] that the effect of the preload between the surfaces, as long as it is kept in the μN range, has no relevant influence on the transferred momentum. The testing campaign has been performed by setting finger accelerations up to 10mm/s^2 and measuring the resulting transferred momentum to the TM.

In Fig. 11 the results of the testing campaign are shown. It can be noticed that the mean values show a good agreement with the proposed theoretical model, that foresees a decreasing momentum with the acceleration of retraction. A relative dispersion of the results, typical of the adhesive phenomena, is highlighted by the maximum values for each acceleration. In this case, this issue is emphasized by the choice of relatively rough contacting surfaces intended to minimize the adhesive interactions. The best data fit yields a C_1 constant equal to 5×10^{-10}J/√m, that is in good agreement with estimated values of both $r_0 \approx 10^{-6}$m [11] and $\Delta U \approx 10^{-12}$ J [12]. The C_2 constant takes into account the non-conservative effects that still affect the contact even at the very low preloads experimented.

The standard deviation of the sets of measurements for each acceleration decreases with the acceleration, down to the theoretical value expressed in Eqn. 3 and calculated in section 3.1. This means that at the highest accelerations explored the dispersion of the measurements is due to the identified noise sources (seismic and readout noise) rather than to the physical phenomenon that is measured. At the lower end of the acceleration range the dispersion increases, showing a lower repeatability of the conservative adhesion. Noticeably, no transferred momentums have been measured larger than the requirement, set at 10^{-5}kg m/s.

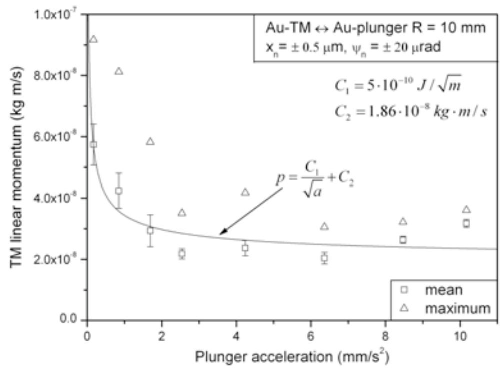

Figure 11. Estimated linear momentum transferred to the TM for different finger accelerations.

A relevant point that must be addressed is the estimation of the effect of the seismic motion on the detachment of the two bodies. If the kinetic energy that the finger would assume with respect to the TM under the forcing action of the seismic motion transmitted by both the suspending and the pulling fibers is comparable with the binding energy, this would assist the adhesion rupture. The relative velocity of the finger with respect to the TM is estimated by means of the transfer functions from the seismic horizontal acceleration to the relative velocity. The relative kinetic energy is calculated as follows:

$$E_{k,relative} = \frac{1}{2} m_{reduced} \left\langle v_{relative}^2 \right\rangle \approx \frac{1}{2} m_{fg} \int_{-\infty}^{\infty} S_V(f)df \quad (5)$$

where $m_{reduced}$ is the reduced mass of the TM-finger pair (nearly equal to the finger mass m_{fg}), $\left\langle v_{relative}^2 \right\rangle$ is the mean square relative velocity between the two bodies and $S_V(f)$ is the power spectral density of the relative velocity. The kinetic energy $E_{k,relative}$ due to the seismic noise results $4\cdot10^{-15}$ J, i.e. 3 orders of magnitude lower than the estimated binding energy ΔU. This means that the kinetic contribution to the detachment is negligible.

4. CONCLUSION AND FUTURE WORK

The present paper focused on the on-ground testing issue of the release phase of the LISA TM on behalf of the dedicated mechanism (GPRM) developed for the technology demonstration mission LISA Pathfinder. The approach is to measure the momentum transfer occurring when two free-falling bodies interacting with surface forces are impulsively separated, in order to investigate the dynamics of release in the absence of gravity. A measuring technique based on two pendulums, suspending the separating bodies, has been analyzed in terms of the capability to accurately reproduce the stress status on the contact patch. Particular attention has been paid to the noise sources affecting the measurement and on the achievable measurement accuracy of a noise optimal-filtering technique. The developed experiment aims at characterizing the transferred momentum to the released TM due to the conservative interactions, therefore low preloads and accelerations of retraction have been experimented. The measured transferred momentums show a good margin with respect to the imposed LISA requirement. The following testing activity of the release phase are finalized to develop a system that enables the preloading of the contacting surfaces up to the actual values applied by the GPRM. The acceleration of retraction shall be increased in order to be representative of the flight mechanism.

5. ACKNOWLEDGEMENTS

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