TESTING THE INJECTION OF THE LISA-PATHFINDER TEST MASS INTO GEODESIC CONDITIONS

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ABSTRACT

LISA Pathfinder is a technology demonstration mission aimed at testing the free-fall purity level of a reference mass (or test mass, TM). Such an object can be used as a geodesic tracker for the detection of gravitational waves and is the core of the Gravitational Reference Sensor (GRS). The low acceleration noise level pursued for the tracker sets tight design constraints on the GRS. Any non-gravitational force has to be reduced to the level of 10 fN in the measurement bandwidth (1-30 mHz).

The TM is firmly constrained by the Caging and Venting Mechanism (CVM) during the spacecraft launch and is then handed over to the Grabbing Positioning and Release Mechanism (GPRM). This mechanism is designed to handle the TM during in-orbit operations and inject it into the geodesic trajectory (or free-fall condition) by means of a quick retraction of two release tips on two opposed sides of the TM. After these operations, the TM residual velocity must be below 5 μm/s, otherwise the GRS capacitive position control is not able to capture and centre the TM in its electrode housing. Due to this criticality, the requirement on the maximum release velocity is verified on-ground both by means of an experimental apparatus (the Transferred Momentum Measurement Facility, TMMF) and by means of simulations. The TMMF is specifically designed to assess the contribution of adhesion between TM and release tips to the total TM momentum. On top of this contribution, any deviation from a symmetrical action of the two opposed release mechanisms determines an extra transferred momentum. Great care must be taken to correlate the experimental results with the in-flight conditions, where a different actuator is used to perform the TM injection. The extrapolation of the experimental results to in-flight conditions and the Montecarlo simulation of the GPRM-TM combined dynamics show the presence of a 2.4 margin factor with respect to the 5 μm/s requirement.

The on-ground measured and simulated performance of the injection phase, its challenges and critical points are here presented and discussed. For the first time, in this paper, the simulations take advantage of the large amount of data available from the testing campaigns.

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Key words: injection into geodesic; release mechanism; adhesion in space; LISA-Pathfinder.

1. INTRODUCTION

The detection of gravitational waves is a challenge engaged by several scientific projects, both on-ground (LIGO[1], EGO[2], GEO600) and in space (eLISA[3], [SAA+13]). In particular, the in-flight detection requires novel technologies to guarantee the free-fall purity of the geodesic trackers required to resolve the waves [AAA+11, AAA+12], such that an entire space mission was conceived as technology demonstrator. The mission selected for this challenge is called LISA-Pathfinder (LPF) and is scheduled for a launch in 2015 [ESA13].

A free-falling or drag-free object is defined by the absence of all the interactions with the environment except for planetary gravity. The main critical point in drag-free technology is therefore the reduction of spurious forces under a limit, which depends on the scope of the mission. This limit is particularly tight in the LPF mission, where the maximum non-gravitational force has to be on the order of 10 fN in the measurement bandwidth (1-30 mHz) [AAA+11]. The reference object in LPF is a gold coated 2 kg Au/Pt cube called the Test Mass (TM). This cube is located in the Gravitational Reference Sensor (GRS) and is enclosed in a box called Electrode Housing (EH, Fig. 1). The internal surface of the EH is covered by a set of electrodes, capable of measuring and actuating

[1]Laser Interferometer Gravitational Wave Observatory
[2]European Gravitational Observatory
[3]evolved Laser Interferometer Space Antenna

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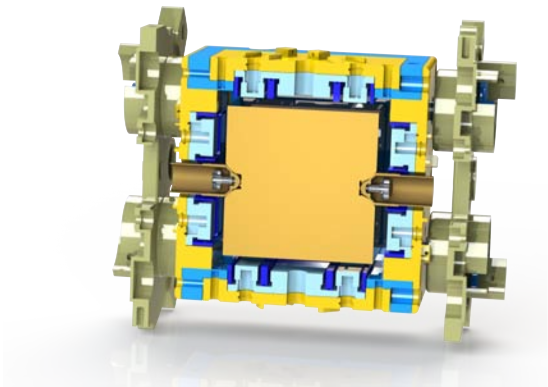

Figure 1. Cut view of the EH and the TM grabbed by the GPRM.

the TM attitude and position. The LPF scientific payload called LISA Technology Package (LTP) hosts two GRS, and the relative displacement between the two TM along one axis is measured by means of an interferometer. An operational criticality in drag-free technology, and in LPF above all, is the transition between the spacecraft launch and science phases [BFML10]. In LPF the TM is heavily constrained by the Caging and Venting Mechanism (CVM) during launch to avoid damages to the EH and the TM itself. Similar mechanisms have been designed since the earliest days of drag-free technology [HMD76]. Once ready for the science phase, the TM is handed over to the Grabbing Positioning and Release Mechanism (GPRM, [MNR$^+$07, NRN09]) and centered in the EH while the CVM constraining fingers are removed. The GPRM grabs the TM with two opposed plungers engaging the TM on a pyramidal recess on two opposed surfaces. The plungers are then slowly retracted while two release tips, coaxial with the plungers, move forward engaging a flat surface on the bottom of the recess. Finally, the tips are quickly (about 40 mm/s) retracted by means of two piezo-stack actuators, in order to release (i.e. inject into free-fall) the TM. The TM configuration after this procedure has to be included in the following bounds:

- $\pm$ 200 μm of offset along x, y and z;
- $\pm$ 5 μm/s of linear velocity along x, y and z;
- $\pm$ 2 mrad angle around x, y and z;
- $\pm$ 100 μrad/s rate around x, y and z;

This is the GPRM requirement: there is some margin at system level. After the release, only the limited (1 μN) force applied by the electrodes is available for actuation. If the configuration exceeds the limits described above, the control system is unable to capture and center the TM.

Due to the mechanism configuration and the tight requirements on the TM centering, the major criticality is associated with the linear momentum rather than the angular. The GPRM transfers momentum to the TM upon the release phase if its overall action is not symmetrical on both sides (i.e. the two force applied vs. time profiles are not equal). Two contributions to the linear momentum are identified: the effect of adhesion [JKR71] between the release tips and TM and the asymmetry of the retraction time profile of the two tips. The first contribution may be relevant, because adhesion between tips and TM is enhanced by the presence of gold coating and the vacuum environment, and is highly asymmetric due to its low repeatability. The second effect is mainly related to the presence of a compression contact force between tips and TM, before the release, which is again converted into momentum if the retraction of the tips is not symmetric. Both aspects need to be addressed.

For a space mechanism, careful testing is the best way to demonstrate its capability to fulfill the assigned task in its planned life [FSS03]. Only an environment that reproduces the operational conditions is able to reveal some of the faults that may be encountered. This is particularly true in this case where the usual qualification and validation procedure has been associated to a testing campaign aimed at the assessment of the adhesion effect on the TM injection into geodesic. These data are included in a recently developed model of the GPRM [BCZ13] and used to run a large set of simulations following a Montecarlo approach. A similar procedure is performed to assess the effect of a non-symmetrical GPRM action. The statistical approach allows for the estimation and discussion of the worst case.

2. EXPERIMENTAL SETUP AND RESULTS

A facility specifically designed to test adhesion in LPF-like conditions has been developed at the University of Trento. The system, called TMMF, is broadly described in [BBB$^+$11, BBC$^+$11] and is depicted in Fig.(2). The goal of the TMMF is to test adhesion in a vacuum environment where the TM is substituted by a mock-up suspended on a 1.1 m-long pendulum. The TM mock-up is engaged by a tip mock-up actuated by a piezo stage. The tip mock-up is loaded against the TM, while this is held by a blocking system on the opposite face, unloaded and then quickly retracted. During this operation the motion of both the TM and tip mock-ups are measured by an interferometer and a Differential Optical Shadow Sensor (DOSS, [ZHS]) respectively.

The main subsystems of the TMMF are the vacuum chamber, the TM mock-up, the release tip mock-up, the plasma source (for cleaning the surfaces), the active damping table, the actuators (capable of moving the suspension point and the piezo stage along and around several axes), the sensors (interferometer, DOSS and an optical lever for the angles), the high speed camera and the blocking system needed to hold the TM during the application of the preload. In order to reproduce the in-flight conditions, the TM is loaded with 300 mN and then un-

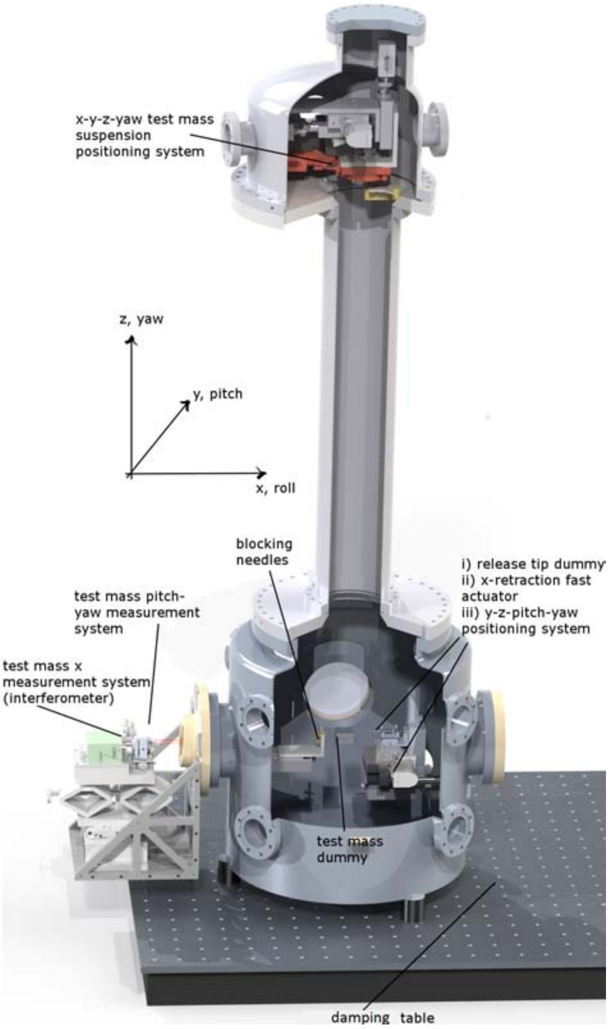

Figure 2. Cut view of the TMMF.

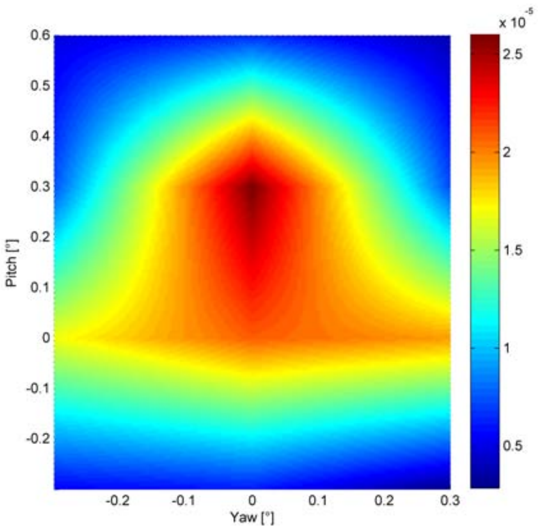

Figure 3. Measured impulse in Ns as function of yaw and pitch angles.

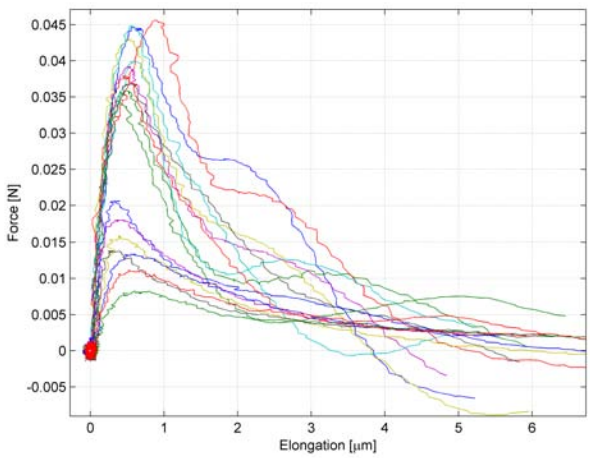

Figure 4. Set of force-to-elongation functions derived from the experimental campaign with a 0.089 kg TM mock-up.

loaded to a nominally 0 force, which is kept for a couple of seconds. The quick retraction is performed shortly afterwards. The experimental procedure is repeated many times. In order to find the direction where the retraction of the tip is really normal to the TM surface several yaw and pitch angles are explored (Fig. 3). If the retraction is not normal, the rupture of the adhesion bond is made easier by gravity, that can not give the same contribution in space.

The swing motion of the TM mock-up is measured by the interferometer and the impulse transferred to the pendulum can be estimated both by the long-period (about 2s) swing oscillation and by deriving the TM motion and looking for the steady-state velocity in the short timeframe (few milliseconds) after the action of the impulse. More recently, the data analysis is performed in order to estimate the adhesion force, which constitutes the physical quantity ruling the transfer of momentum. By means of data filtering and differentiation through the Savitzky-Golay filter [SG64] the TM acceleration (i.e. the adhesion force per unit mass) is combined with the elongation at the contact and the force profile is obtained (Fig. 4).

A small preload (< 10 mN) remains between the mock-ups before the retraction, which is balanced by the blocking system. At the moment of retraction of the tip mock-up, the preloaded blocking system pushes the TM away contributing to the overall TM acceleration and momentum:

$$I_{pl} = F_{pl}\sqrt{\frac{M}{k}} \qquad (1)$$

where k is the needles stiffness, assumed linear, M is the TM mock-up mass and F_{pl} is the residual preload. The force-to-elongation functions obtained by direct differentiation of the measured signals are then affected by a systematic additive error and by the measurement noise. A procedure to disentangle adhesion from this effect and

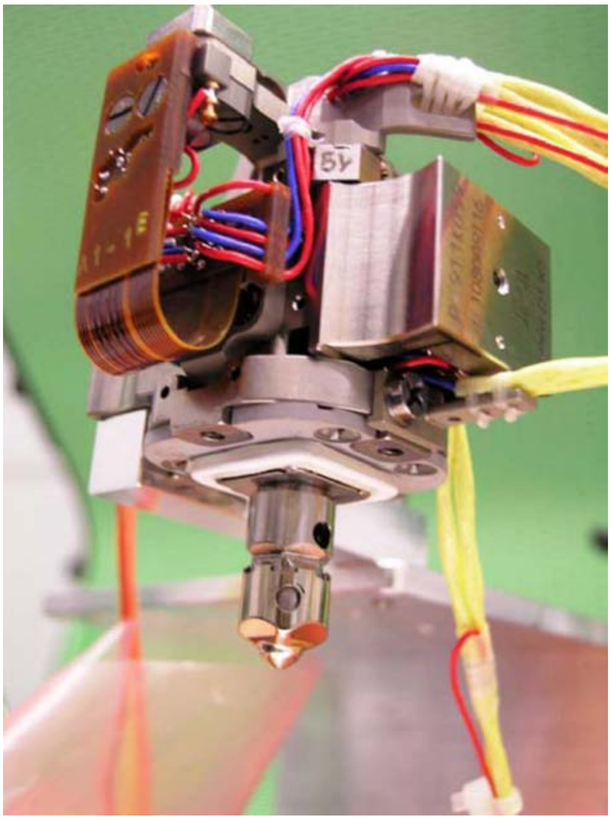

Figure 5. Grabbing, Positioning and Release Mechanism, GPRM (courtesy of RUAG Schweiz AG, RUAG Space).

from the disturbance is under development. However, the experimental curves shown in Fig. (4) are used as an estimation of the adhesion effect.

3. EXTRAPOLATION TO IN-FLIGHT CONDITIONS

The tip mock-up actuator in the experimental facility is different from that actuating the flight release tip (Fig. 5). The retraction velocity commanded on-ground is around 4 mm/s while the GPRM is retracted at about 40 mm/s. For this reason the experimental results have to be extrapolated to in-flight conditions by means of a physical model of the release mechanism. The basic assumption in the extrapolation is that adhesion does not depend on the rate of the elongation. The developed GPRM mathematical model is described in [BMAN11, BCZ13]. It is a lumped model that joins both the electrical and the mechanical dynamics. The release tip is moved by a piezo-stack loaded against a set of washer springs. The nominal input is a 120 V voltage (extended tip) short-circuited to 0 to command the retraction. The equations of motion describing the in-flight release phase, inclusive of adhesion, are:

$$R\, C_a\, \dot{q}(t) + q(t) - T_{em} x_T(t) = C_a\, E(t) \qquad (2)$$

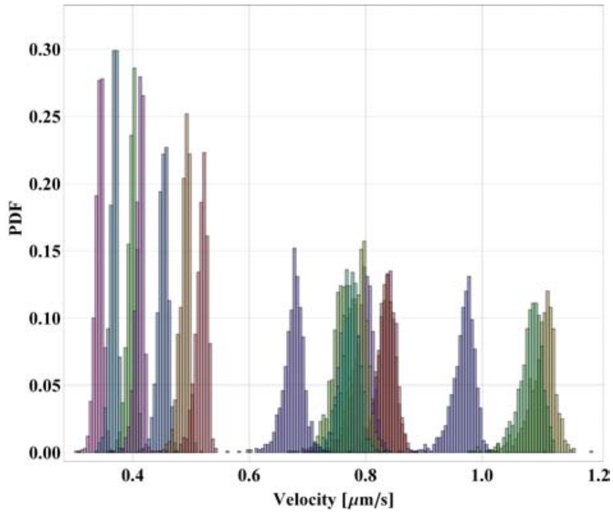

Figure 6. Histogram plot of the release velocity obtained with 18000 simulations.

$$m\, \ddot{x}_T(t) + b\, \dot{x}_T(t) + \left(k + \frac{T_{em}^2}{C_a}\right) x_T(t) + \frac{T_{em}}{C_a} q(t) + F_{adh}\left(x_T(t) - x_{TM}(t)\right) = 0 \qquad (3)$$

$$M\, \ddot{x_{TM}} - F_{adh}\left(x_T(t) - x_{TM}(t)\right) = 0 \qquad (4)$$

where the voltage E(t) is the input, q(t) the charge accumulated on the piezo, $x_T(t)$ is the release tip position, $x_{TM}(t)$ the motion of the TM, R is the resistance of the electrical circuit, C_a the capacitance of the piezo-stack, T_{em} the electromechanical transducer (or the piezo effect), m the mass of the release tip and half piezo-stack, b the damping, k the stiffness (result of the washer spring and piezo elasticity combined effect), M is the TM mass (1.96 kg) and $F_{adh}\left(x_T(t) - x_{TM}(t)\right)$ is the force-to-elongation function. In this case this function is a piecewise function connecting all the experimental points derived from the TMMF data. The uncertainty on the GPRM model parameters is taken into account by a covariance matrix and by running the simulations with a Montecarlo approach. The adhesion effect can not be statistically randomized because there are no parameters, in this case. However, the large number of $F_{adh}\left(\Delta l\right)$ obtained in the TMMF allows to run several simulations with different adhesion conditions. Due to the low repeatability of adhesion, a 1-sided release is here considered, where adhesion acts between one tip and the TM and the other tip does not apply any pull force. This approach is conservative and worst case. The results of 18000 simulations is shown in Fig. (6). The 99.73 % (3 σ if the distribution is normal) worst-case velocity is 1.135 $\mu m/s$ which is below the GPRM requirement. Each of the discrete peaks shown in Fig. 6 is associated with one of the $F_{adh}\left(\Delta l\right)$ curves shown in Fig. (4). It is worth remarking that a couple of assumptions has been made. The force-to-elongation function is considered independent on the rate of retraction and the experimental data are collected with about 10 mN residual preload before the retraction of the tip. This assumption is based on the nominal passover/release sequence, however larger residual preloads (300 mN) are measured during the on-ground GPRM passover sequence tests.

4. ANALYSIS OF THE VIOLATION OF SYMMETRY

The asymmetry of adhesion is already addressed by considering a 1-sided release. However, the analysis of the combined dynamic of the retractions on the 2 opposed tips and of the TM suggests another possible issue. In the presence of a residual pushing force between TM and tips before their retraction, any asymmetry in their motion profile converts into a net force on the TM and a momentum is transferred to the TM (this contribution is also called catapult effect). The effect of adhesion and of residual preload on the overall momentum are uncoupled if the TM displacement during the retraction of the tips is neglected. Let's consider the worst case of the adhered tip retracted first, exerting an adhesive pull which makes the TM move at 10 μm/s (twice as much as the requirement). Even in such a condition, during the action of the adhesive pull (lasting less than 1 ms, total retraction time) the TM displacement would be 0.01 μm, which is less than 10 % of the indentation of the tip in the TM with a 300 mN load (0.113 μm). This means that the indentation at the opposed tip (not adhered and time-lagged) is almost unaffected and the preload force is nearly at the equilibrium value (300 mN). The following retraction of the remaining tip generates a push on the TM whose effect is nearly unaffected by adhesion and is active until it is completely retracted. As a consequence, the contributions of adhesion and of residual preload are uncoupled and may be simply added. With this assumption the contribution to the TM release velocity combining 2 equal retractions, delayed of a certain amount of time, and with a residual preload is:

$$v_{pl} = \frac{F_{pl}\tau}{M} \tag{5}$$

where v_{pl} is the release velocity, F_{pl} is the load between the tips and the TM, τ the delay and M the TM mass. Assuming the 5 μm/s of the requirement, and the expected worst-case 300 mN of preload, the maximum delay, without any adhesion, is 32.6 μs. In order to estimate the possible time lag between the two tips, the commanding voltages applied to the two GPRM piezo-stacks by its control unit have been measured. Fig. (7) shows the measured command voltages applied on the GPRM flight model (FM) release mechanisms (a similar plot is available for the Engineering Qualification Model). It is worth noting that the real input is not a 120 V ideal inverse step and a drop time of 1-1.5 μs is required. It is clear that, more than a pure time lag, the two signals are affected by a different drop time.

The time profiles of the commanding voltages are included in Eq. 2, 3 and 4. Following the statistical approach used for adhesion, the combined non-symmetry/residual preload effect is simulated with a

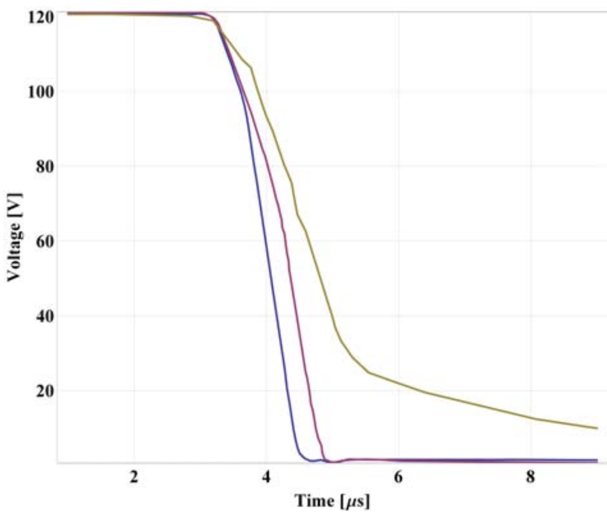

Figure 7. Measured voltages applied on the GPRM FM breadboard.

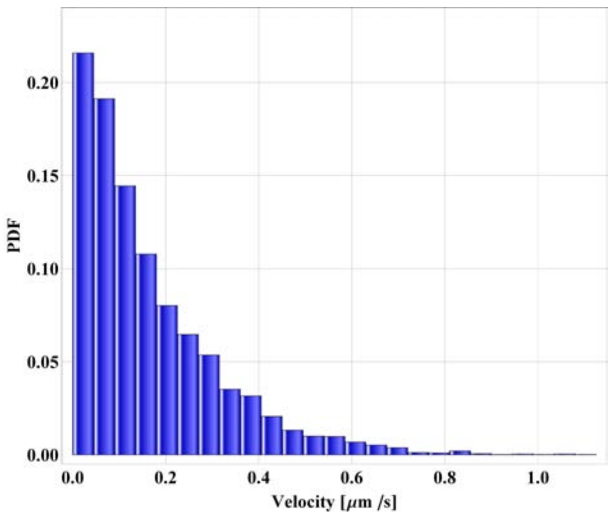

Figure 8. Residual velocity probability density function for the residual preload of 300 mN (no adhesion).

Montecarlo procedure. The voltage drop time is randomized with a probability density function extracted from the available data. The input is described by a piecewise function like:

$$E(t) = \max(0, 120 - ldv\ t) \tag{6}$$

where ldv is the slope of the dropping voltage. The probability density function of ldv is extracted from the data measuring the slope between 120 and 60 V, where the tip retraction is most effective. The input profiles are assumed to be synchronized (i.e. same starting time), but not symmetrical. Fig. (8) shows the probability density function of the residual velocity. The 99.73 % of the simulations is below 0.97 μm/s with a 300 mN preload. The effect of preload is shown in Fig. (9).

As stated above, the models here presented both for adhesion and for the catapult effect depend on the TM motion

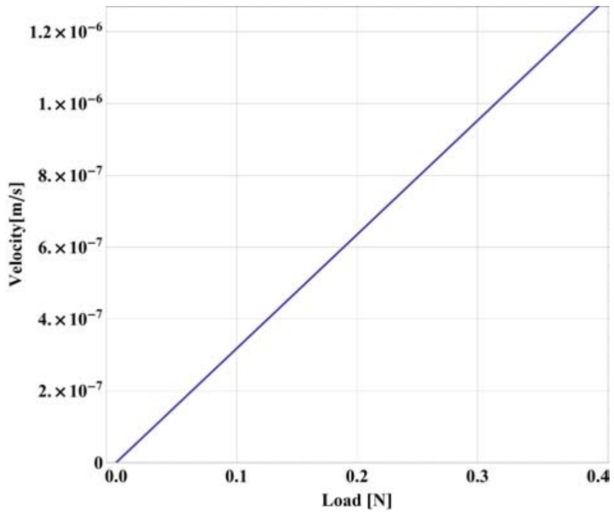

Figure 9. 99.73 % limit release velocity as a function of preload given the inputs measured on the FM, without adhesion.

and on the tip retraction. As the motion of the tip is nearly unaffected by adhesion back-action, adhesion force and its impulse only depend on the motion of the tip, and are unaffected by the motion of the TM. Therefore the two contributions to total momentum are uncoupled and can be simply added. Taking the 99.73 % worst-case effect of residual preload and asymmetry of retraction and the same worst-case velocity produced by adhesion alone, an overall velocity of 2.15 μm/s is calculated. This number is below the requirement by a factor 2.4.

5. CONCLUSION AND FINAL REMARKS

The LISA-Pathfinder mission presents several critical points. One of them is the injection into geodesic trajectory of its cubic reference objects (or test masses). The velocity of each of these objects, once all the constraints are removed, is upper-limited to allow the capture and centering on behalf of the capacitive actuation. The Grabbing Positioning and Release Mechanism (GPRM) is the device in charge of the injection with a compliant residual velocity, which means a velocity below 5 μm/s. However, some additional margin on such a limit is present at system level. In order to check this problem, any phenomenon capable of transferring momentum from the GPRM to the test mass has to be analyzed. The main drivers of momentum are identified as adhesion with the release tips and the non-symmetrical GPRM action on the 2 sides of the test mass. The preliminary effect of adhesion based on a test campaign performed on a reduced mass mock-up and on a direct estimation of adhesion (not based on a physical model) is estimated, by means of a large set of simulations, in 1.135 μm/s. A non symmetrical 300 mN residual preload applied on the test mass during the release provides 0.97 μm/s. 99.73 % of the simulations are below this limit assumed as worst case. A raw estimation of the release velocity is performed by adding the two contributions, obtaining 2.15 μm/s. This estimate is compliant with the requirement, but shows some limits. Adhesion is extrapolated between different elongation rates (TMMF vs. GPRM) and has been experimentally analyzed with an initial preload around 10 mN. Moreover, the data available for the symmetry of tip retraction are still limited and do not take into account nonsymmetries due to the mechanical part of the mechanism. On the other hand, the results achieved are encouraging. Even if some uncertainties remain, the worst case velocity after the action of the release mechanism appears compliant with the requirement with a reasonable margin. Due to its criticality, the developed GPRM design constitutes a key result for LPF and a clear starting point for the future eLISA space mission.

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