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Abstract. The cold gas micro-propulsion system that will be used during the LISA-Pathfinder mission will be one of the most important component used to ensure the "free-fall" of the enclosed test masses. In this paper we present a possible strategy to characterize the effective direction and amplitude gain of each of the 6 thrusters of this system.

1. Introduction

One of the aims of the ESA's LISA-Pathfinder [1] (LPF) mission is to demonstrate the feasibility of maintaining, in space, a *Test Mass* (TM) in *free fall* (i.e., following an orbit only subjected to the solar system gravitational forces) with a residual acceleration of less than $3\text{x}10^{-14}$ m/s^2 around 3 mHz. As such, LPF is a mission whose aim is to test "key technologies" that will be used for the detection of gravitational waves by LISA type [2] space missions.

In order to ensure the *free-fall* of one of its enclosed free floating Test Masses (see TM$_1$, figure 1), the LPF on-board system measures the position of this TM with respect to the satellite body and endeavors to maintain, via a system of micro-thrusters, the spacecraft (S/C) centered on this TM. This micro-thruster system is constituted of 6 cold gas thrusters, identical to those currently used for the Gaia [3] mission. The assumed direction cosines of the thrust provided by the thrusters is given in lines 2-4 of Table I. As the solar pressure is used to limit the number of thrusters necessary to control all 6 degrees of freedom (displacement along the X, Y and Z axis and the torques around each of those) their direction along the Z axis, which points towards the Sun, are all positive.

Because of the importance of this thruster system in ensuring the *free-fall* of TM$_1$, it is essential to have the possibility to characterize, in flight, the performances of each thruster. This paper presents a strategy, based on ideas suggested by W.Fichter [4], to characterize the mean direction and amplitude gain of each of the thrusters.

2. Characterizing the mean direction and amplitude gain of each thruster

The basic idea of the strategy is to apply simultaneously, in addition to the *in-loop* actuation signal, a sine force of given amplitude and frequency to each thruster. This will force a displacement of the S/C which, detected through the position error signal of TM$_1$, will be countered by the *in-loop* control system (DFACS : Drag Free and Attitude Control System) whose task is to maintain the S/C centered on TM$_1$ (and also to maintain a proper *attitude* with respect to the Sun). The quantity:

$$\vec{F}_{tot}(t)=\vec{F}^{CMD}_{DFACS}(t)-M_{S/C}\frac{\partial^2\vec{x}_{TM1}(t)}{\partial t^2} \tag{1}$$

where $M_{S/C}$ is the mass of the S/C and $\vec{x}_{TM1}(t)$ is the position vector of TM$_1$ with respect to the S/C, will reflect the force applied by the thruster system. The second term on the right hand side of equation 1, which accounts for the phase and gain imperfections of the control loop, is, for the actuation frequencies considered in this study (~ mHz) very small (~ 10^{-11} N) compared to the first one (~ 10^{-6} N).

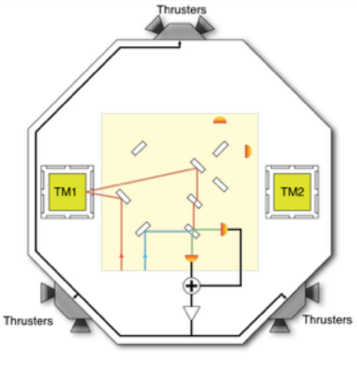

Figure 1: Schematic representation of the thruster control system.

It should be noted that $\vec{F}_{Tot}(t)$ will reflect the *effective* thrusts (amplitudes and directions) of the system and not the *out-of-loop* thrust and direction which is artificially applied.

Applying simultaneously different frequencies on each of the 6 thrusters and filtering $\vec{F}_{Tot}(t)$ at these corresponding frequencies allows characterization of the whole system in just one sequence.

The analysis of the direction of $\vec{F}_{Tot}(t)$ will therefore measure the direction of the thrust and its amplitude will characterize the gain of the thruster.

The data analyzed in this work comes from simulations using ESA's mission simulator SOVT for LPF which contains a complete description of the thruster system, including a non-linear dispatching algorithm, and amplitude and flutter (directional) noise.

The characterization sequence lasts of the order of 25000 seconds and figure 2 shows the three components of the DFACS requested force, $\vec{F}_{DFACS}^{CMD}(t)$. One can observe that the forces on X and Y have an average value close to zero (the solar pressure has negligible impact on these) whereas the force on the Z axis has a mean value close to 20μN, necessary to counter the solar pressure.

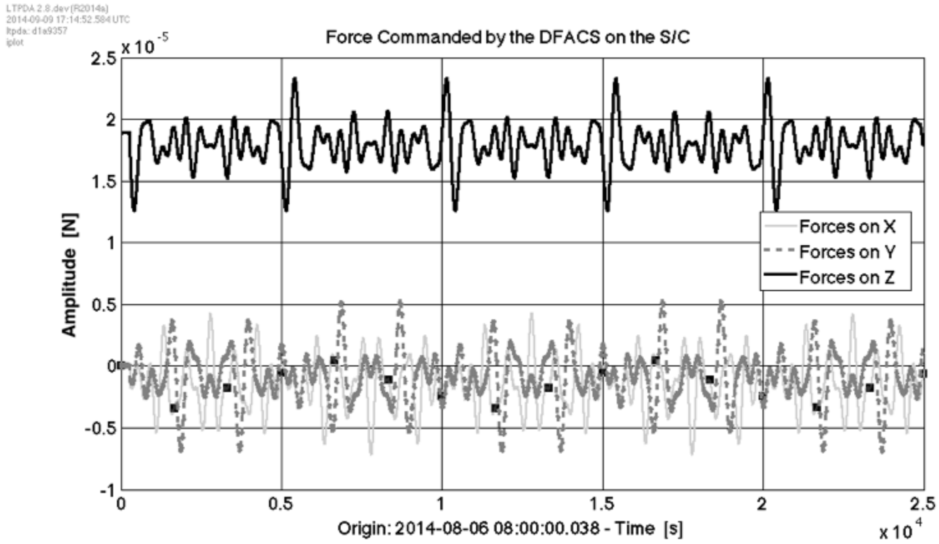

Figure 2 : Force commanded by the DFACS on the X,Y and Z (solar) axis.

Figure 3 shows, as an example, the time series obtained from $\vec{F}_{Tot}(t)$ after filtering with a band pass filter in order to isolate the S/C movement associated to the actuation of thruster N°3. The Fourier transform of this time series is used for the *PSD* method, whereas the 3D analysis of $F_X(t)$, $F_Y(t)$ and $F_Z(t)$ is at the basis of the *PCA* method (see next chapter).

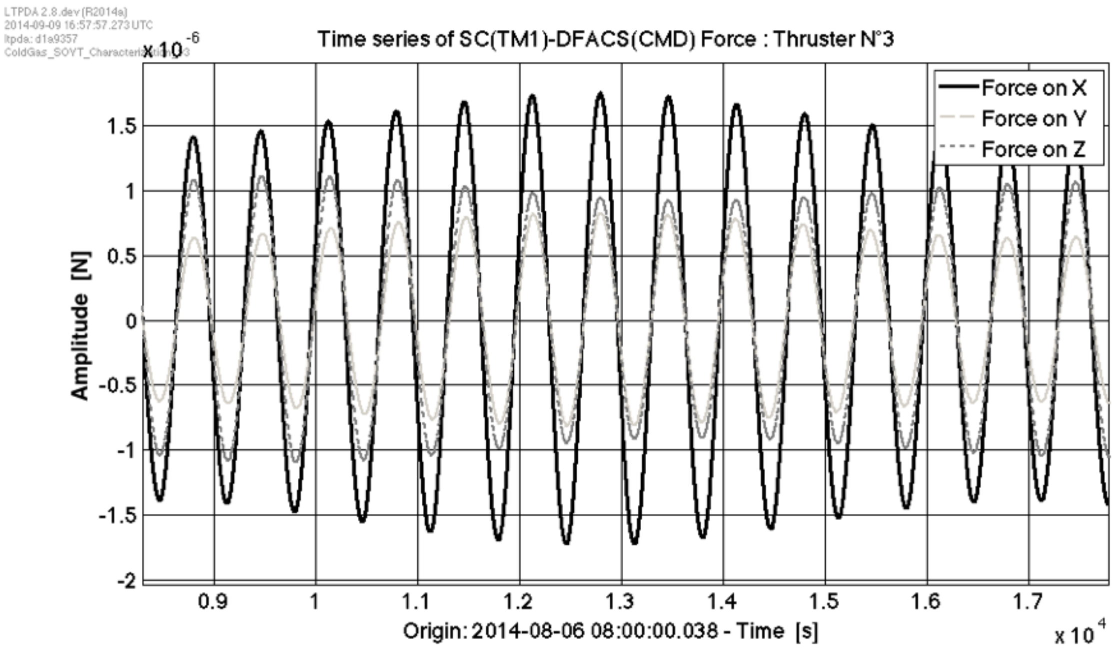

Figure 3 : A sample of the $\vec{F}_{Tot}(t)$ time series after filtering at 1.5 ± 0.12 mHz when characterizing thruster N°3.

3. Analysis Results

The mean direction and amplitude gain of the thrusters can be studied with various techniques.

After having filtered the $\vec{F}_{Tot}(t)$ time series at the frequency associated to a given thruster, one can perform a Fourier transform resulting in a three component Fourier vector ($\vec{F}_{Tot}(f)$) whose direction can be compared to the assumed direction of this thruster. This is the PSD method. In this case the applied thrust can be measured by the norm of $\vec{F}_{Tot}(f)$.

Another technique consists in considering the $\vec{F}_{Tot}(t)$ times series, regularly sampled (1 Hz), as so many points in a 3D space and perform a Principal Component Analysis (PCA) on these. Such a method yields 3 eigenvectors whose largest one will give the average thrust direction.

Table I. gives, on line 4, the difference between the assumed direction and the measured one for the two methods. Lines 2 and 3 give the frequency and thrust requested on each thruster.

Table I : Actuation frequencies, requested thrust and direction error for each thruster.

Thruster N°	1	2	3	4	5	6
Frequency (mHz)	1.10	1.30	1.50	1.70	2.10	2.70
Requested thrust (μN)	2.00	2.00	2.00	2.00	2.00	2.00
Direction using PSD (°)	0.35	0.62	0.55	0.31	0.10	0.11

4. Summary and Future Developments

The results presented show that a relatively simple strategy can, in less than 12 hours, give a precise characterization of the thruster system that LPF will have on board. The mean direction values are probably precise enough for what is needed but a more complete analysis of the two methods used (PCA and PSD) should allow for an estimate of the associated errors. The error on the direction is of particular interest as it may allow to estimate the *flutter noise* (fluctuation of the direction of a thruster) which is a difficult quantity to measure in a ground based test facility.

An extension of this strategy can also be used to measure the spectral shape of the amplitude noise of individual thrusters. This has been tested for both white and colored noise and will be published shortly.

It should also be noted that these same techniques can be applied to characterize the Colloidal Micro Newton Thruster (CMNT) system that will fly aboard LPF as part of the NASA-provided Disturbance Reduction System payload [5].

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