Development of a Micro-Thruster Test Facility which fulfils the LISA requirements

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Abstract. In the context of investigations for a sufficient attitude control thruster for LISA, we have developed a thruster test facility which consists of a highly precise thrust balance coupled with plasma diagnostics. In parallel to the test facility development, investigations to downscale a High Efficiency Multistage Plasma Thruster (HEMP-T) are also being carried out. The thruster has been used to demonstrate the measurement capabilities of the facility. The setup allows a parallel operation of all instruments and can also be used for other types of µN propulsion systems including cold gas thrusters. The thrust balance consists of two pendulums. As read out a heterodyne laser interferometer is used. Differential wave front sensing (DWS) enables the measurement of the pendulum tilt which, via suitable calibration using an electrostatic comb, can be converted to a thrust. The whole setup is a symmetric configuration enabling a common-mode rejection of the dominant noise sources (e.g. seismic noise etc.). The thrust balance has a demonstrated precision of 0.1 µN. Based on our unique design, this precision can be attained down to 10\textsuperscript{-3} Hz. Thus, the measurement setup is especially suitable for characterising the thrust noise of potential eLISA propulsion candidates. We give an overview of the design, the present performance and the future plans.

1. Introduction

In 2009 the Laboratory for Enabling Technologies (LET) at AirbusDS Friedrichshafen started a research and development project to investigate possible micro-Newton thrusters for highly precise attitude control of satellites for Laser Interferometer Space Antenna (LISA) like missions. Within the framework of the project, a feasibility study to downscale a High Efficiency Multi Stage Plasma Thruster (HEMP-T) to micro-Newton thrust is performed. A schematic thruster assembly is given in figure 1 a). It depicts a cut through the cylindrical HEMP-T. The dielectric discharge chamber (in yellow) is surrounded by a system of periodically poled permanent magnets. This typical magnet stack forms a special magnetic field topology which separates the discharge chamber into several magnetic cells. Furthermore, the field confines the plasma on the rotation axis of the thruster. Therefore, the plasma has ideally almost no interaction with the dielectric walls surrounding the discharge chamber. On the left side of the scheme (upstream end of the discharge chamber) the anode is mounted. The anode operates as the gas inlet as well. On the right side of the scheme (downstream) a neutraliser cathode is placed.
the anode and the cathode the potential difference ranges from 300 V to 2000 V. The HEMP-T works as an electrostatic thruster i.e. the thruster relies on coulomb forces to accelerate a propellant of charged particles. HEMP-Ts use xenon as propellant, therefore, the plasma consists of positive charged xenon ions. The ionisation of the neutral xenon gas to the plasma is realised by bombarding the plasma with electrons (electron bombardment thruster).

For the development of micro newton thrusters and for the basic research of micro-Newton ion propulsion, a sufficient test facility is required. Such facilities are available e.g. at the University of Giessen [7]. The standard set of diagnostic hardware consists of a Faraday Cup, or Faraday Array, and a Retarding Potential Analyser (RPA). The tools are used to characterise the basic parameter such as ion current density, or ion energy of a thruster plume, which allows an indirect thrust measurement. But also direct thrust measurement systems are in use [8] [2] [9]. Especially the challenging requirements of future space telescope missions like LISA require a detailed characterisation of the potential thruster candidates. In particular, the direct measurement and the characterisation of the thrust noise is imported to get reliable informations of the Attitude and Orbit Control System (AOCS) jitter, but as far as we know the existing thrust balances are not long term stable enough to characterise micro-Newton thruster in the complete LISA measurement bandwidth. Therefore, we developed a highly precise and highly stable micro-Newton thrust balance which fulfils the LISA requirements, especially in point of thrust noise.

2. Measurement Setup
The developed thrust balance is a double pendulum balance. The applied force (or thrust) of the thruster under test, deflects the measurement pendulum. The detected pendulum deflection can be converted into the applied thrust by multiplication with the pendulum spring rate. In general, the performed measurements are a differential measurement between the two fully symmetric pendulums. This allows the suppression of seismic and thermal mechanical noise which leads to the unique stability of the presented setup. The balance, in back view, is shown in figure 2 c). The balance consist of the pendulum arm (d), the major balance structure and the bearing (b) and two dielectric mirrors (c). Each pendulum is damped by an eddy current brake (a). A plastic tube (h) is used as gas supply for the investigated thruster. The thruster is not shown in figure 2 c). An electro static comb (f) [5] is used to calibrate the balance. A heterodyne
Figure 2. Picture of the whole micro-Newton thruster test facility. Image a) shows the facility from outside, in b) the inner space of the vacuum tank is shown. Picture c) shows the micro-Newton thrust balance in back view.

interferometer is used as translation sensor. Due to the use of quadrant photo diodes, differential wave front sensing allows an independent measurement of the pendulum tilt in addition to the normal translation measurement. The thrust balance can be used in two different operation modes, open loop and closed loop. In open loop operation the pendulum translation is directly measured, the difference between the equilibrium of the pendulum and the measured translation can be converted to the applied thrust. In closed loop operation each pendulum is actively controlled to neutral position by a voice coil. As controller input the DWS signal is used.

The balance is placed in a 1500 litre vacuum chamber. Two turbo molecular and one cryo pumps with together 11400 litre/s pumpage are used to evacuate the tank. Therefore, the basis pressure is $4 \times 10^{-7}$ mbar and the working pressure, with 0.5 sccm gas ballast, is $1 \times 10^{-6}$ mbar. The vacuum chamber is shown in figure 2 a). To decouple the facility from the ground, the vacuum tank is mounted on an ITEM structure which is supported by four optical isolators. In addition to the thrust balance, a basic set plasma diagnostics is also part of the test facility. It consists of 15 Faraday Cups and one RPA. The instruments are mounted on a rotatable jib arm, which can rotate 180° around the thruster. Figure 2 b) presents the internal space of the vacuum tank, with the thrust balance and the plasma diagnostic. The facility design allows a parallel operation of the thrust balance and the plasma diagnostic. Thus, a comparison of the direct and of the indirect thrust measurement can be performed.

In parallel to the thrust balance development we continued the downscaling of the HEMP-T principle to micro-Newton Thrust. The characterisation of the different micro-HEMP-T designs were performend in the presented facility, as well as in the thruster test facility at the University of Giessen [7].
3. Results
As result of the parametric experimentally downscaling campaign a thrust of 66 µN by an ISP of 200 s were achieved, but on higher thrust levels (around 400 µN) the thruster has an ISP larger then 1500 s [6]. The operation space of the micro-HEMP-T is presented in figure 1 b).

Figure 3. Summary of the balance performance. The blue plot presents the performance of one undamped pendulum. The purple plot shows the performance of a damped pendulum. The Black curve is the requirement. The red plot shows the performance of the full balance setup with active common mode rejection.

To characterise the thrust balance and the whole test facility, we performed a set of different tests with and without active thruster. Figure 3 summarises the thrust balance performance and the effect of different parts of the thrust balance assembly, in point of thrust noise. The presented measurements were performed with the fully integrated setup. A deactivated thruster was mounted on the balance. The cryo pump had to be deactivated during the measurements because of the still insufficient noise shielding between cryo pump and vacuum chamber. The Power Spectral Density (PSD) presents the thrust in µN, normalised by the frequency in $\sqrt{\text{Hz}}$ versus the frequency. The black plot presents the targeted balance requirement, which is the LISA thrust noise requirement [4]. The blue curve presents the noise measurement of a single undamped pendulum versus a fixed mirror, hence no common mode rejection occurs. The observed eigenfrequency of the pendulum is 0.77 Hz, this is close to the estimated eigenfrequency of 0.8 Hz. The amplitude of the free swinging pendulum is the dominant noise term of the measurement resolution. Down to lower frequencies pink noise occurs and limits the resolution in point of long term stability. The purple plot presents the performance of one damped pendulum versus a fixed mirror (no common mode rejection). The damper suppresses the eigenfrequency. Therefore, at higher frequencies the noise level decreases on 1.5 order of the magnitudes, compared to the blue plot. At lower frequencies pink noise dominates the PSD.
The noise measurement of the whole setup, which means two damped pendulums, is shown as the red plot. Therefore, the noise level decreases of one order of the magnitude. Down to lower frequencies the rise of the noise level is reduced. The plot illustrates that the assembly is stable enough to fulfil the LISA requirement.

4. Conclusions

The micro-Newton thruster test facility at AirbusDS in Friedrichshafen, which consist of a highly precise thrust Balance and a plasma diagnostic system, is operational. The balance fulfils the LISA requirement in point of thrust noise and thrust resolution. This allows the characterisation of potential micro-Newton thruster candidates for LISA. First tests with an active thruster were performed [3]. Moreover, the results of our HEMP-T downscaling were given. Especially on higher thrust levels the micro-HEMP-T is able to operate with an ISP over 1500 s, which is promising. Therefore, we will continue the downscaling of the HEMP-T principle. In the next months, an advanced noise shielding of the cryo pump will be installed, this will lead to thrust measurements with permanent running cyro pump. It is planned to perform the characterisation of different micro-Newton thrusters in our micro-Newton thruster test facility.

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