Verification of the FOTEC µN Thrust Balance at the ESA Propulsion Lab

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Abstract: Within the ongoing development of the mN-FEEP thruster under ESA Funding, the Start-Up Performance of the thruster has been evaluated. Tests have been performed with a large number of emitter and critical parameters like the starting voltage and the initial firing homogeneity have been conducted. Furthermore, the initial priming of the emitter after the Start-Up has been investigated. The test results have been collected in a database and correlated to geometrical parameters of the emitter. This correlation has then been used to assess the possibility to model and predict the Start-Up behaviour of the thruster prior to testing.

I. Introduction

At FOTEC a torsion-based µN thrust balance has been developed to characterize field-emission electric propulsion (FEEP) and miniaturized pulsed plasma thruster (µPPT) propulsion systems [1, 2, 3, 4, 5]. Depending on the operation mode (deflection or force-feedback), the thrust balance is able to measure forces of up to 6 mN whereas the total capacity of the thrust balance is 13 kg thruster weight (see Fig. 1).

Depending on the load, the momentum of inertia is changing which in turn affects the response time of the system. This enables the characterization of small to medium size propulsion systems. The thrust generated by µPPTs only lasts for several µs and cannot be resolved by the thrust measurement system. In [6] the detailed investigation on the characterization of pulsed thrusters can be found. For FEEP propulsion systems with constant thrust levels the low response rate of the thrust measurement system can be accepted in general.

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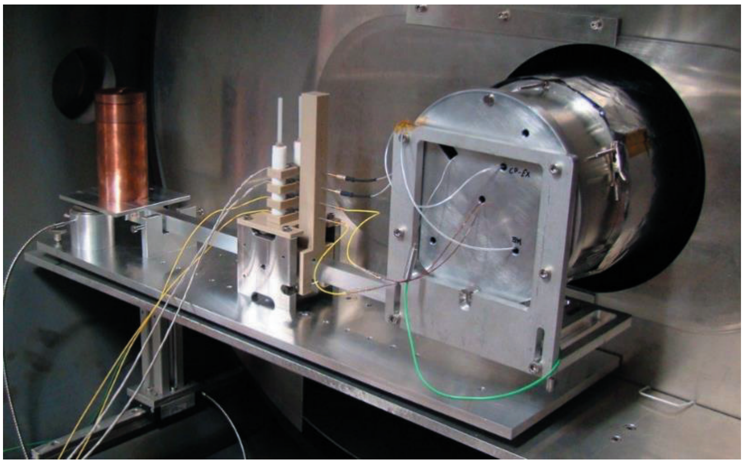

Fig. 1 4th generation µN Torsion thrust balance with testing the mN-FEEP thruster (both developed at FOTEC).

II. Calibration and Reference Forces

Apart from intrinsic values of the thrust measurement system like load capacity, thrust measurement range, resolution and noise or stability, external calibration and verification is crucial for the reliability and credibility of the gathered results.

If the magnetic damping system is removed the spring rate of the bearings can be calculated from the measurement of the oscillation frequency if the total moment of inertia is known [6]. The drawback of this method is that the spring rate is subject to change under different loading conditions. In addition this procedure can only be performed at the beginning of the test campaign by using test weights and the determined spring rate has to be considered as being constant throughout the entire campaign. However tests have revealed that indeed the spring rate can be altered by ambient conditions like the temperature, vacuum pressure, and propellant feeding tubes or electrical cables.

The ability of generating reference forces during the test campaign help to calibrate or readjust the thrust balance during operating without the need of opening the vacuum chamber or changing the configuration. In addition the concept of force-feedback can be applied to keep the beam of the balance in resting position which does not require the knowledge and stability of the spring rate anymore.

A. Magnetic Force Actuators

There are various ways to generate reference forces such as the utilization of electrostatic or electro-magnetic effects. The good controllability of the electrical voltage or current enables precise simulation of externally applied thrust. Typically a so called voice coil consists of a solenoid and a soft magnetic rod positioned within the coil. The ferro-magnetic rod is pulled into a solenoid if current is applied. At low force levels when the magnetic material is still far from saturation, the force is proportional to the excitation current. At ESTEC a voice coil is being utilized for calibration purposes (see Fig. 4, right bottom) which is driven by a precision current source [6]. For a perfectly homogeneous magnetic field the force generated does not depend on the position of the rod.

In practice due to inhomogeneities and non-linearities the positioning accuracy does affect the overall performance of the magnetic force actuator which needs to be considered in the uncertainty budget estimations. Moreover the permeability of the ferro-magnetic material is temperature-dependent and care has to be taken not to expose the solenoid to any generated magnetic fields throughout the tests that might be generated by current-carrying wires. The presence of ferro- or diamagnetic materials in the vicinity of the voice coil can also compromise the accuracy of the force actuator. Still another problem comes up when dealing with ferromagnetic materials: the remanence. Even when the exterior magnetic field is switched off completely a certain remaining magnetization within the material persists. This magnetization can also result from other magnetic field like the Earth magnetic field.

B. Electrostatic Force Actuators

An electrostatic comb consists of at least two flat overlapped electrodes. When voltage is applied between these electrodes an attractive force is generated. The more electrodes are being utilized, the higher forces can be generated. The voltage between the electrodes can accurately be controlled and since no dielectrics are involved, no additional factors (permittivity or its temperature dependency) need to be utilized.

In practice the distance between the electrodes needs to be small, otherwise the generated force might be too small at reasonable voltage levels. Since the force is inverse proportional to the distance, any deviations strongly affect the strength of the force and thus the accuracy of the force actuator.

C. FOTEC Electrostatic Force Actuator

The presented electrostatic force actuator can be slightly modified in order to reduce the sensitivity to the positioning accuracy. A parallel plate capacitor is formed (see Fig. 2, green) and initially no dielectric is put between the electrodes. If a dielectric is inserted between the electrodes (red thin bars), the capacitance and thus the electrostatic energy is subject to change. One can show that the force does not depend on the position of the dielectric if the electric field is homogeneous. In practice this assumption is valid for small distances between the capacitor electrodes. A material featuring high permeability, good thermal stability and low susceptibility to outgassing or water absorption needs to be utilized. At FOTEC Zirconia is therefore being utilized. In the current setup forces of up to 500 μN at voltages below 2 kV can reliably be generated.

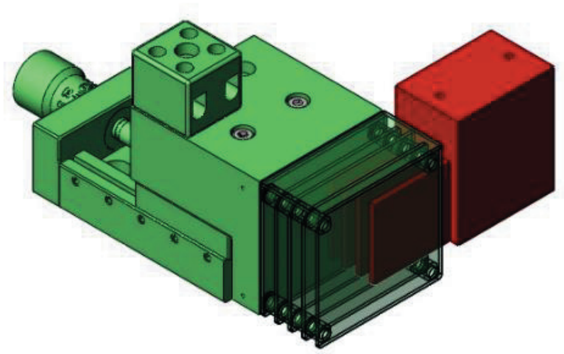

Fig. 2 Electrostatic force actuator developed at FOTEC. The linear table enables exact relative positioning.

Before the FOTEC force actuator is being mounted on the thrust balance, it is put on a precision balance (Mettler Toledo AX 504 balance with vacuum-compatible modifications) in order to find the calibration factor between the applied voltage and the generated force (see Fig. 3). Throughout the test the chamber is evacuated in order to prevent forces resulting from ion winds or corona discharges.

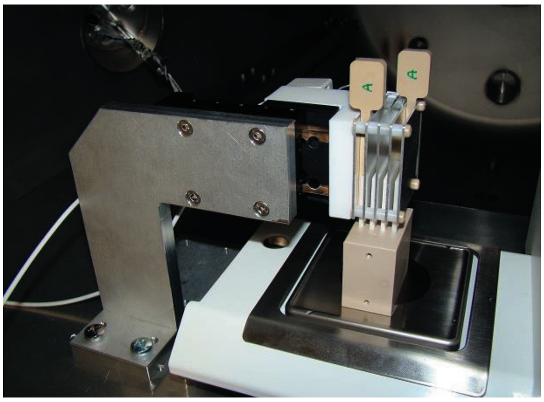

Fig. 3 Setup for calibration of the force actuator on the Mettler Toledo AX 504 balance.

III. Verification Campaign at ESA

Since the accuracy of the entire thrust measurement system strongly depends on the accuracy of the force actuator a careful calibration procedure is required before any test campaign. Despite that, the ultimate verification of the thrust balance and the verification of the calibration process including data processing and curve fitting can only be performed by the use of a reliable and well characterized thruster as reference.

In November 2014 a test campaign was performed at ESA Propulsion Laboratory (EPL) using the FOTEC thrust measurement system and the MOOG VPS03-002 cold gas thruster. This thruster has already been utilized for the comparison of different ESA thrust balances [7].

The FOTEC thrust balance was operated in two different measurement modes: displacement and force-feedback. In displacement mode, the force actuator is not utilized during the thrust measurements. It is only required to measure the spring rate of the bearings by comparing the applied force and the measured deflection. The beam of the balance is deflected when the thruster is operating and the displacement distance is measured with an optical transducer. Consequently the generated torque and thus the generated thrust can be computed. In this mode all four thrust points 30 µN, 150 µN, 450 µN and 800 µN, at which the cold gas thruster had be characterized before, can be measured.

In force-feedback mode the electrostatic force actuator is being utilized to compensate the force generated by the thruster. The control loop tries to maintain the beam in resting position when the torque and counter torque are equal. Knowing the force required for compensation, the force generated by the thruster can be computed. In this mode it is not required to know the spring rate of the bearings. So any influence on them caused by ambient temperature or load is negligible. In addition the accuracy of the optical sensor is not affecting the overall accuracy of the thrust balance since the read-out value of the sensor is constant when the beam remains in resting position. Since the force actuator is only able to generate forces of up to 500 µN, the highest thrust point of 800 µN cannot be measured in that mode.

D. MOOG VPS03-002 Cold Gas Thruster

The micro proportional thruster (MPT) VPS03-002 developed by MOOG UK is a cold gas thruster which is controlled by the internal piezo valve. Depending on the applied voltage (mV range) the propellant flow and thus the generated thrust can precisely be controlled. The MPT has been tested several times in the EPL in 2006, 2008, 2011, 2012 and 2014 and test results were published in dedicated test reports [8, 9, 10, 11, 12, 13, 14, 15].

For precise characterization of the MPT, it is mounted on a Mettler Toledo AX 504 balance which had been modified by ESTEC to guarantee good vacuum compatibility (see Fig. 4, thruster on top of the adapter). In addition a force actuator is utilized to validate the test setup was also positioned on the balance during the entire test campaign.

Fig. 4 Setup for calibration of the MOOG VPS03-002 Cold Gas Thruster on the Mettler Toledo AX 504 balance [7].

A schematic of the test setup is given in Fig. 5. The gas feeding line is connected through a set of 1/8” Swagelok connectors. A flexible tubing is introduced in the feeding line to prevent any influence of the pressurization of the nitrogen pipe on the thrust measurement. The nitrogen gas is fed to the thruster through a dedicated feeding system where the mass flow rate and the pressure of the gas at those points are monitored. Thermocouples are connected to the MPT (one on thruster body) as well as on the balance support and on the vacuum facility wall to monitor the environmental conditions around the thruster during the test. A detailed description of the test setup and procedures can be found in the test reports and in [7].

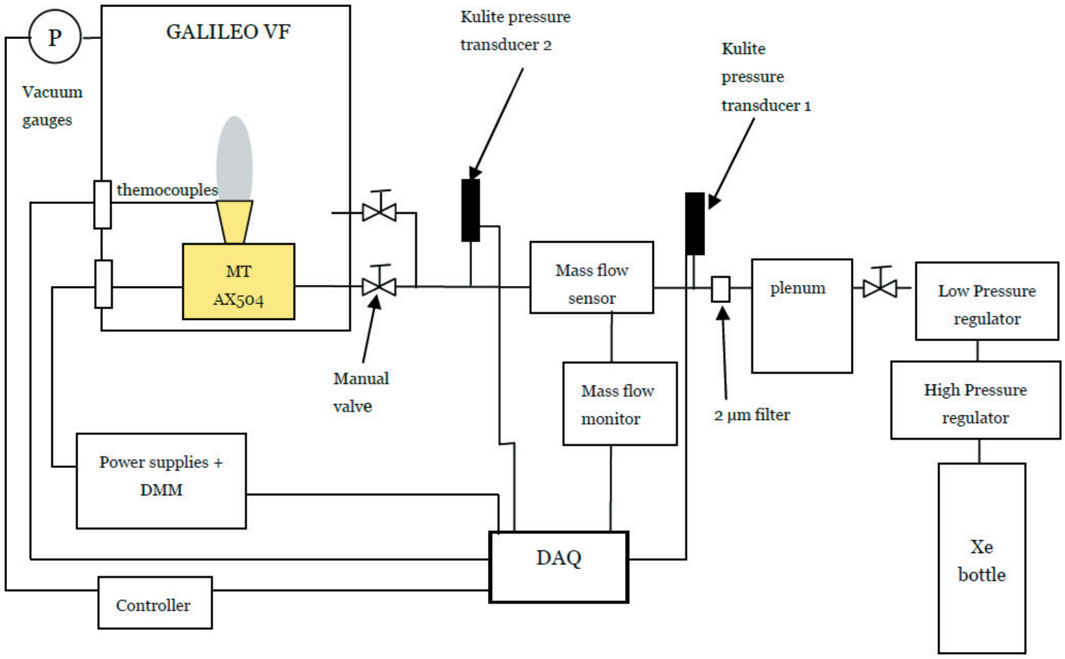

Fig. 5 Schematic of the test setup with the MPT tested in the Galileo vacuum facility [7].

In Tab. 1 the test results for four thrust points and their uncertainty is given [16]. For the uncertaintly computation a coverage factor of $k = 2$ (95%) was utilized. A full set of uncertainty factors can be found in [7].

Pressure set point [mV]	**Thrust [μN]**	**Uncertaintly [μN]**	**Background pressure [mbar]**
5.0	36.76	1.39	9×10^{-6}
20.0	191.21	1.47	4×10^{-5}
40.0	439.88	1.77	8×10^{-5}
70.0	838.18	1.54	1.4×10^{-4}

Tab. 1 MPT test results and uncertainty budget summary.

IV. Test Preparation

In order to operate the MPT, the thruster has to be supplied with propellant via a flexible feeding tube and electrical control lines. Additionally thermocouples are attached to verify thermal equilibrium during the tests. When measuring in the μN regime, any cable or particularly tubes affect accuracy and may introduce phantom forces.

For electrical feed-throughs special contacts dipping into a Galinstan (Galium, Iindium, Tin alloy) filled reservoir have been developed and tested at FOTEC. A detailed description and test results can be found in [6]. To supply the MPT with propellant a fixture with a thin and flexible hanging Tygon tube has been developed (see Fig. 6). Tests with different tube pressurization level have shown only little influence on the performance of the thrust measurement system.

In the frame of the verification campaign an additional electro-static force actuator was attached to the thrust balance to verify closed loop operation with force-feedback (see Fig. 6, right bottom).

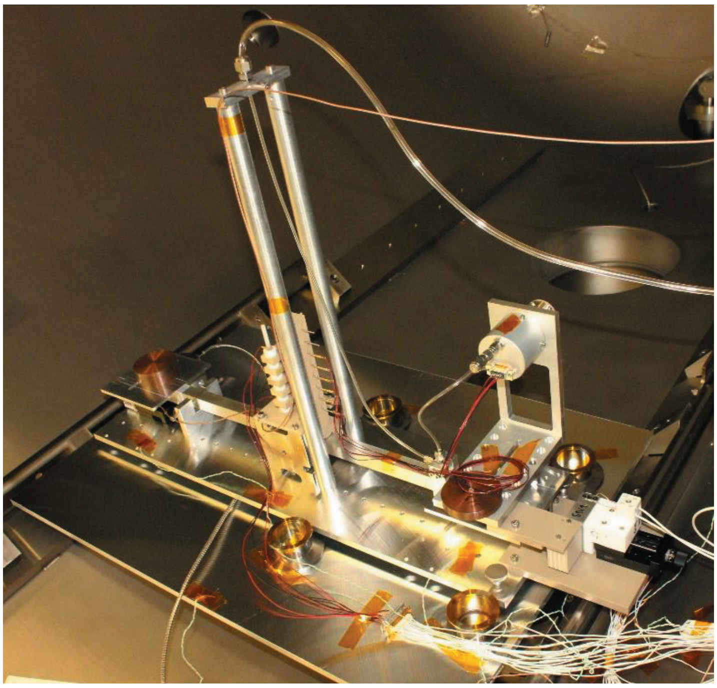

Fig. 6 Test setup of FOTEC thrust balance with MPT at ESTEC.

During a previous verification campaign in 2013 a similar test setup was utilized but in a smaller vacuum chamber (Galileo chamber at ESTEC). The distance between the nozzle of the MPT and the chamber walls was less than 40 cm during that test. Analysis of the test results have revealed that there is a great influence of the gas flow on the thrust measurement system. The results were not conclusive and showed great influence of the exact position of the balance, the vacuum pressure and the gas flow rate (respectively the commanded thrust). Analysis of the setup and post-processing of the data resulted in the assumption, that at these low pressure levels (less than 10^{-6} mbar) the model of continuous gas at a uniform pressure has to be discarded. Instead the path of the gas molecules from the thruster to the chamber walls and back to the thrust balance generated an additional torque which led to a phantom force. For the second test campaign in 2014 a protection cover has been manufactured to prevent any influences arising from ambient gas flow. Only a small aperture for the MPT is utilized.

As described in section II the electrostatic force actuator developed at FOTEC utilizes the physical effect that the dielectric is pulled into a charged capacitor. Since the charges are separated at the surface of the dielectric, an additional force towards the electrodes is observed. Only if the dielectric is equally spaced from the surrounding electrodes and perfectly parallel the additional force vanishes. During calibration when the force actuator was put on the Mettler Toledo balance, this force component did not affect the measurement due to internal bearings of the balance which only allow vertical movement of the tray. In contrast, if the force actuator is mounted on the thrust balance, this additional force causes an additional torque resulting non-linear measurement errors. Therefore the force actuator needs to be put right below the beam resulting in no net torque since any attraction between the dielectric and the electrodes is in radial direction adsorbed by the spring bearings.

E. Uncertainty Budget

The spring rate of the bearings can be computed as follows:

$$k = \frac{F_{\mathrm{FA}}\, x_{\mathrm{FA}}\; x_{\mathrm{S}}}{x}$$

with F_{FA} denoting the applied force by the force actuator, x_{FA} the distance of the force actuator from the pivot, x_{S} the distance of the optical sensor from the pivot and x the detected deflection. Uncertainties for all these values have been defined and the total uncertainty of the spring rate results in 3.7%. The improper positioning of the force actuator has the major contribution with 3.4%. This results from detailed simulations of the electrostatic forces within the force actuator.

The following misalignments in the setup have been considered: a tilting between the two components of the force actuator of up to 0.2°, a linear displacement in the direction of the balance beam of up to 0.1 mm. Furthermore, a deflection of the balance of 0.015° has been considered, which corresponds to ca. 1 mN thrust in displacement mode.

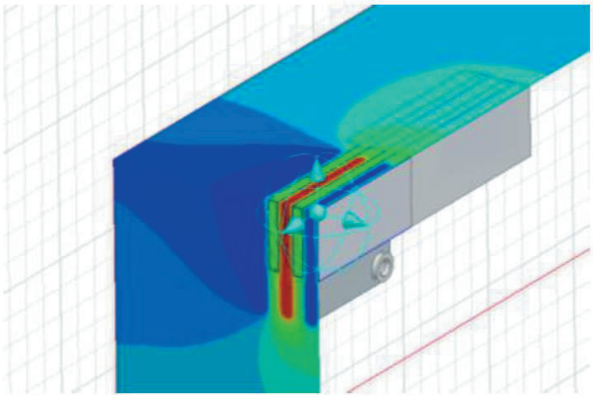

Fig. 7 Simulation of generated forces due to misalignment of the force actuator components.

Tab. 2 summarizes the simulation results from various combinations of these three misalignments. The maximum deviation from the nominal generated force is -3.4% which is utilized in the total uncertainty budget, as mentioned before.

Rotation [°]		-0.2	-0.2	-0.2	0.0	0.0	0.0	0.2	0.2	0.2
Displacement [mm]		-0.1	0.0	0.1	-0.1	0.0	0.1	-0.1	0.0	0.1
Deflection [°]	-0.015	**-3.40%**	-2.80%	-1.76%	-1.78%	-0.91%	0.40%	-0.44%	1.01%	2.97%
	0	-3.26%	-2.06%	-1.67%	-2.16%	0.00%	0.45%	-0.25%	1.42%	3.16%
	+0.015	-3.10%	-2.49%	-1.21%	-1.95%	0.06%	0.37%	0.14%	1.60%	3.01%

Tab. 2 Test results for various misalignment combinations.

If the thrust balance is operated in displacement mode, the thrust is defined as

$$F_{\mathrm{DISP}} = \frac{k\,x}{x_{\mathrm{S}}\,x_{\mathrm{T}}\cos\alpha}$$

whereas x_{T} represents the distance of the thruster from the pivot and α is the misalignment angle of the thruster. In this case the prevailing factor is the spring rate and depending on the deflection x the uncertainty of the determined force is ca. 3.8%. In Tab. 3 the uncertainties of all four thrust points are given.

For force-feedback mode measurements the thrust is computed as follows:

$$F_{FFB} = \frac{F_{\mathrm{FA}}\,x_{\mathrm{FA}}}{x_T\ \cos\alpha}$$

It is obvious that this relation does not depend on the spring rate. Again, the major contribution to the uncertainty budget comes from the force actuator. Depending on the applied thrust and the compensation force F_{FFB} the uncertainty of determined thrust is ca. 3.6%. Tab. 4 lists the uncertainties of all four thrust points.

V. Results

F. Determination of Spring Rate

As described in section III, if the thrust balance is operated in displacement mode, the spring rate has to be determined before the actual test campaign. Since additional torques are observed due to non-perfectly positioned force actuator or the deflection of the beam, several configurations were evaluated in order to measure the spring rate. Two force actuators were utilized whereas the internal force actuator is controlled to generate a reference force of 100 μN, 200 μN, 300 μN, 400 μN and 500 μN. For each of these steps three different forces were applied by the external force actuator to deflect the beam. The spring rate vs. the distance from the resting position of the beam is shown in Fig. 8. Within ± 0.1 mm around the resting position of the beam, the spring rate results in $k = 0.00509 \pm 0.00012\ \mathrm{Nm/°}$.

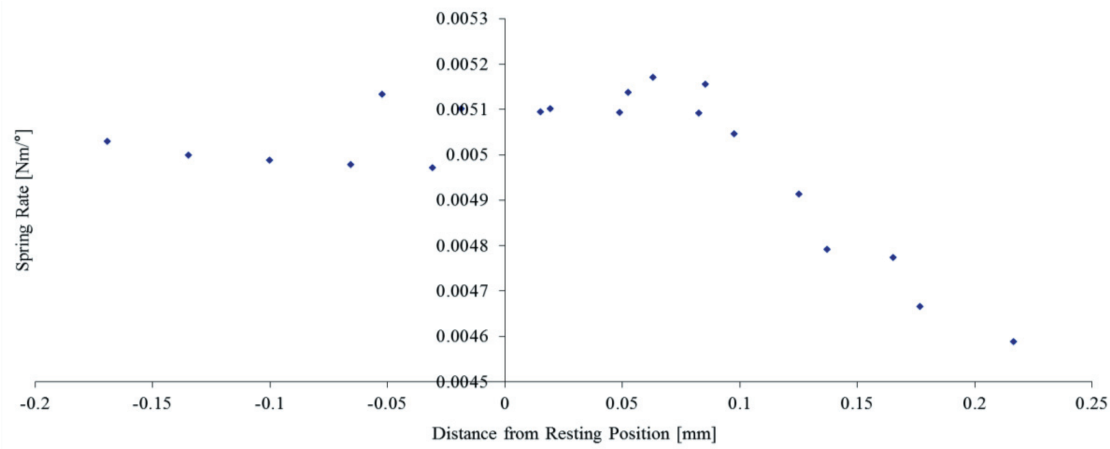

Fig. 8 Measured spring rate as a function of the distance from the resting position of the beam.

G. Verification of Thrust Points

The following table summarizes the results of the test campaign conduced at ESTEC. Here the FOTEC thrust balance was operated in displacement mode and the aforementioned spring rate was utilized to compute the force generated by the MOOG cold gas thruster. Once recognizes that the relative deviation increases with higher thrust levels and finally exceeds the predicted uncertainty limits at the highest thrust point. It seems that, due to the high axial load on the spring bearings, non-linear behavior of the bearings is detectable which has not been considered in the previously presented uncertainty budget.

Ref. Thrust [μN]	Measured Thrust [μN]	Uncertaintly [μN]	Rel. Uncertainty [%]	Deviation [%]
	38.48	2.94	7.64	4.68
36.76 ± 1.39	37.55	2.88	7.67	2.15
	37.10	2.84	7.65	0.92
	197.05	15.10	7.66	3.05
191.21 ± 1.47	195.70	15.10	7.72	2.35
	196.80	15.08	7.66	2.92
	412.40	31.60	7.66	-6.25
439.88 ± 1.77	412.50	31.60	7.66	-6.22
	412.57	31.60	7.66	-6.21
	766.87	58.75	7.66	-8.51
838.18 ± 1.54	765.99	58.68	7.66	-8.61
	766.83	58.74	7.66	-8.51

Tab. 3 Test results obtained in displacement mode.

The following tables shows the results obtained in force-feedback mode. One immediately recognizes the smaller deviation and the higher reproducibility. Since the force actuator is not able to fully compensate the highest thrust point, the beam of the balance still got deflected in that case. This also explains the higher relative deviation compared to the other three thrust points. The given uncertainties cover all measured thrust points.

Ref. Thrust [µN]	Measured Thrust [µN]	Uncertaintly [µN]	Rel. Uncertainty [%]	Deviation [%]
36.76 ± 1.39	37.21	2.64	7.09	1.22
	36.99	2.63	7.11	0.63
	36.68	2.61	7.12	-0.22
191.21 ± 1.47	189.25	13.44	7.10	-1.03
	188.80	13.41	7.10	-1.26
	189.70	13.47	7.10	-0.79
439.88 ± 1.77	434.26	30.84	7.10	-1.28
	434.53	30.86	7.10	-1.22
	434.25	30.84	7.10	-1.28
838.18 ± 1.54	873.88	62.07	7.10	4.26
	876.45	62.25	7.10	4.57
	876.26	62.24	7.10	4.54

Tab. 4 Test results obtained in force-feedback mode.

VI. Conclusions and Outlook

A test campaign at ESTEC was performed in order to verify the accuracy of the thrust measurement system developed at FOTEC. A cold gas thruster was utilized acting as a well-defined reference force applied to the thrust balance. Two different operation modes were investigated and compared: displacement and force-feedback mode. Four different thrust levels were applied and the FOTEC thrust balance was able to measure them at high accuracy. The measurement campaign can therefore be considered as successful. With the use of the thrust balance, thruster modules of up to 13 kg total weight can be characterized with a total uncertainty of 7%.

The gathered results indicate that the force-feedback mode provides more accurate and more reliable results compared to the results gathered in displacement mode. The current FOTEC force actuator provides forces up to 500 µN, therefore the highest thrust point could not be measured properly in force-feedback mode. In the future efforts will be made to increase the maximum force level to at least 1 mN.

The tests showed non-linear behavior of the spring bearings, if the thrust balance is operated in deflection mode. Though this effect is not fully understood yet, the uncertainty budget needs to be revised to take this into account.

Acknowledgements

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