The 250mN Thrust Balance for the DLR Goettingen EP Test Facility

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Abstract: The German Aerospace Center DLR brought into operation a test facility for electric space propulsion in Goettingen, Germany, called STG-ET. This facility has been especially designed for electric propulsion with a vacuum chamber that measures more than 12m in length and 5m in diameter. Besides thruster performance tests the focus is on plume interaction with spacecraft components and on long-term testing. Thrust measurement is a fundamental measurement method for propulsion engine qualification. Ion and Hall effect space thrusters usually produce thrust levels in the milli-Newton range, and thrust balances have to deal with these low values. For the thrust balance of the STG-ET we adopted a thrust balance design based on a counter-balanced, electromagnetic force compensated device. The measurable thrust range is 250mN, but the design can easily accommodate an upgrade to 1N. The maximum allowed thruster assembly mass is 40kg. Several innovative features are implemented in its design.

Nomenclature

cal_{VC} = voice coil calibration factor
EP = electric propulsion
FEEP = field-emission electric propulsion
$Fcal$ = calibration force
Fg = gravitational force
Ft = thrust force
Ivc = calibration voice coil current
STG-ET = Simulationsanlage Treibstrahlen Göttingen - Elektrische Triebwerke
THR = thruster

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I. Introduction

Electric space propulsion engines were used in the past, and are flying in current missions (e.g. ESA's Smart1 or NASA's Dawn), and will be part of new design approaches, like Boeing's new all electric platform concept 702SP. Electric propulsion engines are also gaining more interest especially in the sector of future science missions requesting very low thrust in conjunction with low thrust noise and accurate thrust level control.

The low absolute thrust, compared to their mass, of Hall-effect and gridded ion engines requires long runtimes for fulfilling a given mission. This poses new challenges for qualification and on-ground testing.

II. Brief Description of the Test Facility

The German Aerospace Center DLR operates since many years micro-propulsion test facilities in Goettingen. Besides vacuum chambers for chemical and cold gas thrusters, DLR extended its activities into the field of electric propulsion (Ref). This led to the idea of building the facility STG-ET (Simulationsanlage Treibstrahlen Goettingen - Elektrische Triebwerke).

STG-ET is a dedicated electric space propulsion test facility with a vacuum chamber that measures more than 12m in length and 5m in diameter [1]. Besides engine tests the application focus is on plume interaction with spacecraft components and on long-term testing. Figure 1 shows the STG-ET facility in its dedicated building.

Figure 1. Vacuum chamber of the electric propulsion test facility at DLR Goettingen.

III. Thrust Measurement

Thrust measurement is a basic and crucial method for all kinds of thrusters. The challenge in electric propulsion is that the thrust values are very small compared to the weight of the thruster. Considering ion thrusters we have thrust-to-mass factors of 1/500 up to 1/1000, even worse if adding weight of ancillaries. Requesting a thrust resolution of 0.1% sets the specifications to a maximum load capability of tens of Newton with a resolution well below 1mN. Figure 2 and Figure 3 show some basic options for measuring the thrust of an electric propulsion engine. The simplest way would be to position the device on a scale and let the beam exit vertically upwards (Figure 2a). This approach is possible because high precision scales are available off the shelf. Unfortunately the weight of the engine itself is added to the thrust, which means that a small thrust has to be differentiated from a weight being orders of magnitude higher. In other words, weight and thrust act in the same direction and the dynamic range of the balance must be very high.

Figure 2b, a pendulum, separates weight and thrust. This principle has often been used as it requires only one attachment point (or bearing). A similar design using a dual direct pendulum has been described Nagao et al [2]. One disadvantage is the long string or arm required for sensitive measurements. Another disadvantage is that an arm excursion leads to a rotation of the thrust vector.

Figure 2c shows a different design, the horizontal torsion balance. The thruster assembly sits on an arm held by a vertical wire. The assembly weight is balanced by a counterweight. This holding scheme resembles to a gravitational balance and is very sensitive. Usually this design is employed for µN thrusters (e.g. FEEP's, [3] [4] [8]). The wire may be substituted by a gas bearing for higher load capacity and very low friction [5].

The inverted pendulum shown in Figure 3a is more sensitive than the normal pendulum due to the lack of gravitational back-force [6] [10] [11]. But as it is unstable it needs an active control. The parallelogram inverted pendulum in Figure 3b introduces the advantage of not rotating the thrust vector during displacement. The pendulum arms can be made of spring steel in compression which leads to a high sensitivity [9]. The sensitivity can be increased even more by using the balanced inverted double-pendulum scheme (Figure 3c). A counterweight sits on the lower leg and balances the weight of the thruster assembly located on the upper parallel link.

As this last design has several advantageous properties despite its higher complexity and numerous pivot points, it has been adopted for DLR's EP balance.

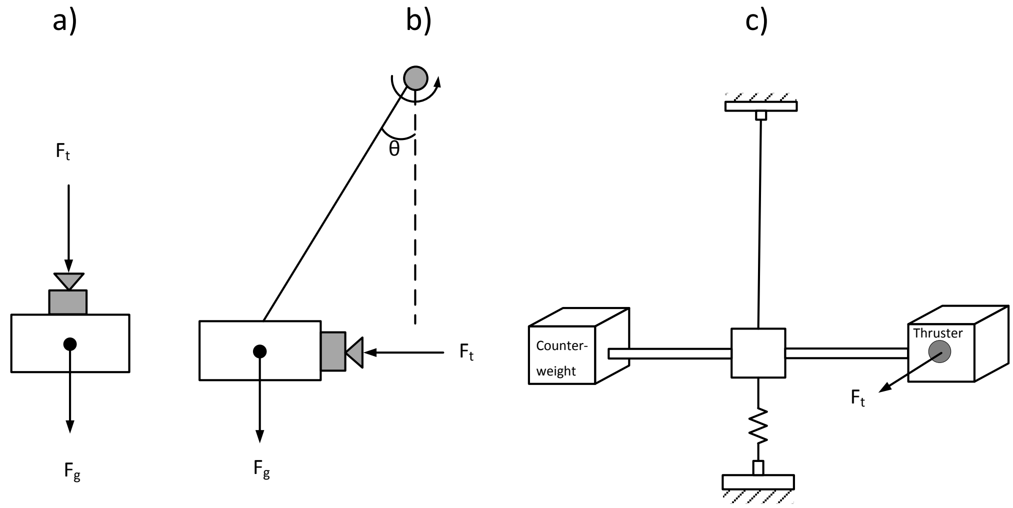

Figure 2. Thrust balance basic designs: a) standard scale principle, b) single pendulum, c) horizontal torsion balance.

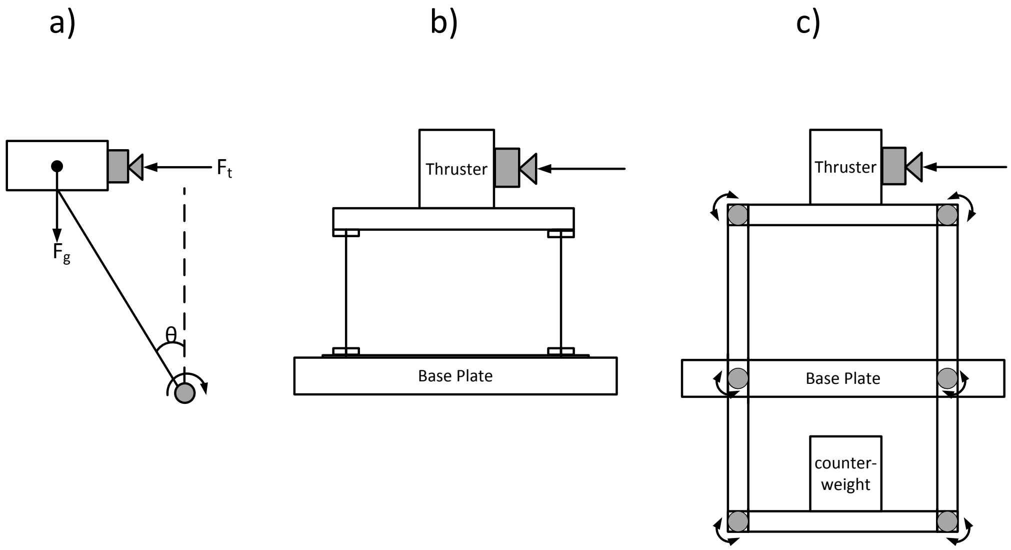

Figure 3. Thrust balance basic designs, continued: a) inverted pendulum, b) inverted double-pendulum, c) balanced inverted double-pendulum.

IV. DLR’s Thrust Balance Design

The new test facility with its large vacuum chamber was designed for thrusters with a somewhat higher thrust, up to a few hundred mN. Accordingly, the thrust balance must be able to measure these values and carry the weight of large thrusters. The primary specification led to 250mN as maximum thrust, and being able to hold 20kg. The company Advanced Space Technologies (AST) has been awarded a R&D contract by DLR to jointly develop a thrust balance.

The specifications finally agreed upon, after some modifications, are listed in Table 1. The balance is with its 130kg quite heavy and can carry thrusters up to 40kg.

The thrust balance has been designed, manufactured and delivered by AST. Tests and optimization are carried out at the DLR.

AST's thrust balance is a counter balanced, electromagnetic force compensated design, which is based on similar design reported earlier [12].

Table 1: Thrust Balance Design Specifications

Maximum thruster mass	40 kg
Thrust range	0-250 mN
Accuracy	2.5 mN
Repeatability	0.5 mN
Resolution	<0.25 mN
Response time (0-90%)	5 s
Settling time	10 s
Drift	< 0.5% of full range per hour
Temperature drift	< 0.1% per degree, measured at thruster platform
Burn-in time	1 hour
Mass	130 kg
Other features	• Calibration with voice coil • Calibration with weight • Calibration in vacuum • Simple upgrade to 1N full range

Figure 4 displays a scheme of the balance where the main parts are highlighted. In red is the thruster-carrying platform, in green the two pendulum arms, which are built as a set of rigid girders forming a stiff parallelogram. The lower platform for the counterweight is colored in olive-green. The connection between table platform and girder is formed by flexible bearings (shown in dark blue) that only allow a movement in the sensitive direction. Orthogonal movements are blocked by the bearing design. All sensitive parts are located inside the enclosed balance while the thruster is placed on top of the table for measurement. The fully shielded design reduces interferences of the propulsion system with the balance electronics.

Figure 5 shows side and front view drawings of the balance with a few dimensions. The balance table is directly connected to a high resolution capacitive displacement sensor. If a force is applied to the table, the parallelogram shifts and the table is displaced relative to the holding structure (Figure 4, frame filled in gray color).

As stated above, the balance is compensated. It has an active control system, which means that the thrust force is compensated by an equal force in the opposite direction so that the excursion is compensated to zero and the pendulum arms stay in a constant position. This control is performed with a position sensor and a voice coil as actuator.

The displacement sensor signal is fed to an electronic circuit that drives a voice coil actuator to compensate the displacement. A special design in the electronic circuit damps out any oscillations of the balance so that this new design doesn't need a further passive damping element like an eddy current brake or an oil tank with paddle. The damping works so well that even vibrations from pumps that are directly connected to a chamber are canceled out. The balance uses a second voice coil to calibrate the system. This will be presented in the next section.

In Figure 6 the active damping feature is displayed. It shows how a short disturbance leads to oscillations, as measured with the displacement sensor (relative units). The effect of electronic damping is visible in the right part of Figure 6, which clearly shows the benefits.

To minimize hysteresis or other disturbing effects, cables and tubes feeding the thruster are mounted in a holder configuration called "cable harp". The cable lengths are adjusted so that the distance between the bending points of a cable or tube is the same as between the corresponding flex bearings.

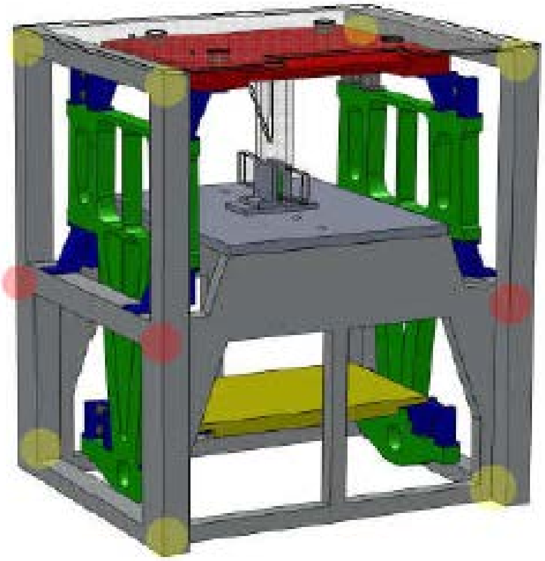

Figure 4. 3d model of the mechanical parts of the thrust balance.

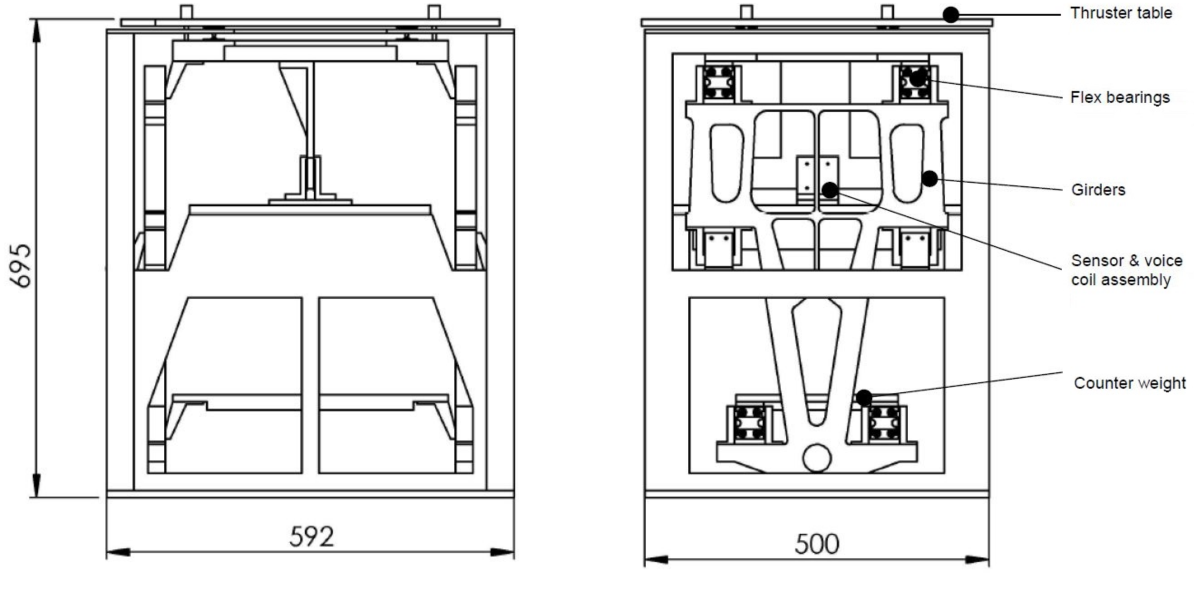

Figure 5. Side and front view drawings of the thrust balance without cover sheets (all dimensions in mm).

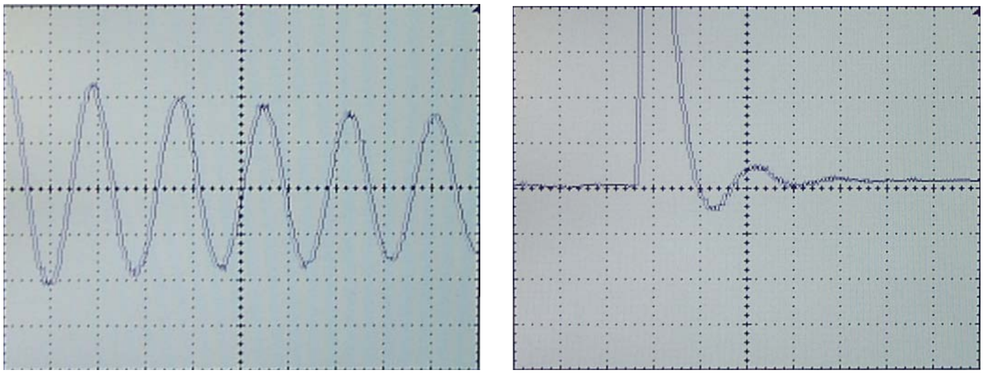

Figure 6. Recordings of position sensor after applying a disturbance (in arbitrary units). Left: oscillations without electronic damping; right: with electronic damping.

V. Calibration

The calibration of the balance is a crucial task and, due to the small forces, poses several challenges. As the vacuum and space environment necessary for thruster operation changes the thermal conditions around and inside the balance, drifts are often encountered. The calibration process should be feasible during an experiment and must not require direct access and a vented vacuum chamber. A first remedy against thermal drifts is to enclose the balance as good as possible with a thermal insulation. This is implemented in AST's design. But still it is important to have the online calibration feature. Our design has two independent calibration paths:

1. Calibration with calibrated voice coil
2. Calibration with direct weighing with test mass

Options 1 uses a voice coil that is powered by a known current and exerts a force pointing in the same direction as the engine's thrust. By powering the voice coil instead of the thruster the electronic system can be calibrated. With its fast response with respect to the exciting current the voice coil method allows the calibration for steady state and dynamic measurements. Figure 7 sketches this method and the arrangement of thrust force, calibration voice coil, and position sensor. The compensation voice coil is not shown here.

The calibration force is given by:

$$F_{cal} = cal_{VC} \cdot I_{VC} \quad [mN]$$

The voice coil calibration factor is given by:

$$cal_{VC} = \frac{force}{current} \quad \left[\frac{mN}{mA}\right]$$

This current-force correlation of the coil has been measured on a commercial microbalance. For this task, the voice coil has to be mounted on the microbalance and powered by known current steps. A result is shown in Figure 8, where the good linearity of the voice coil is obvious. Figure 8 also pictures on the right the voice coil itself.

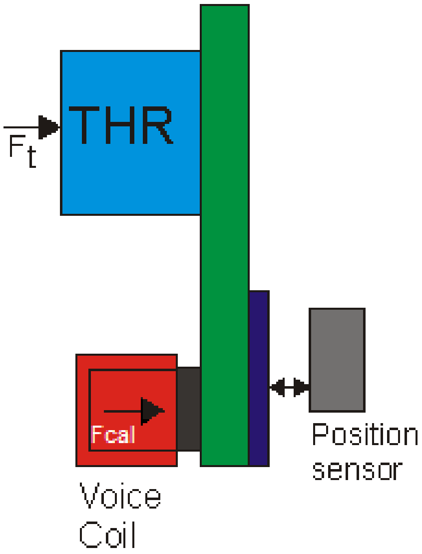

Figure 7. Position sensor and actuator.

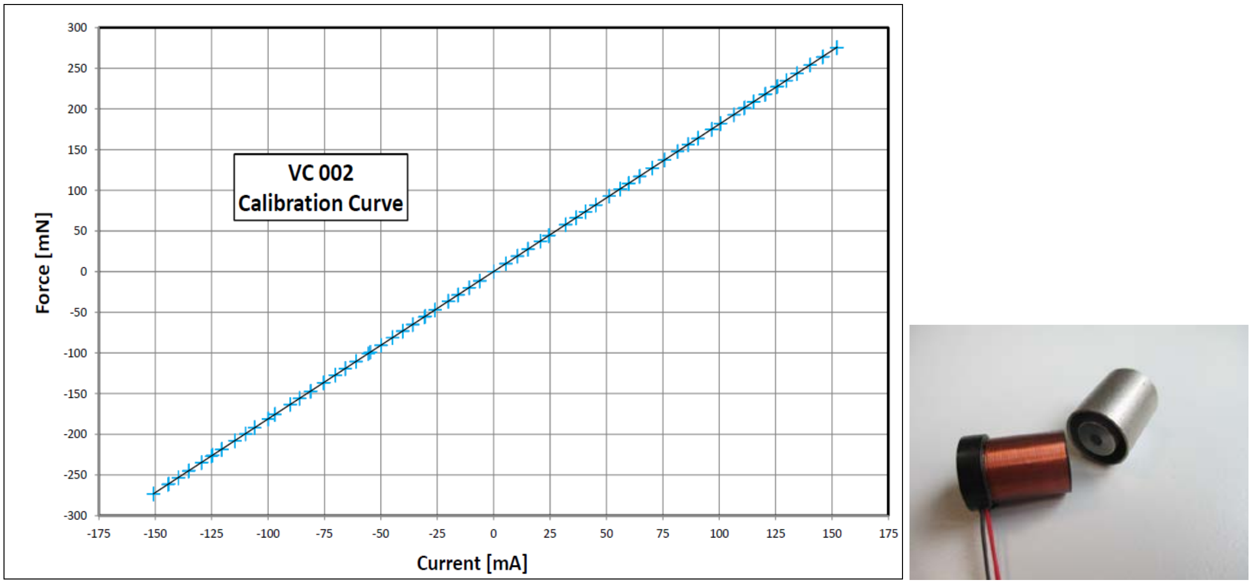

Figure 8. Left: Calibration curve of voice coil actuator measured on a microbalance. Right: voice coil assembly.

In addition to the voice coil calibration the balance is designed for the integration of Option 2, a gravimetric calibrator. This method uses accurately measured masses for a direct calibration. The balance has a device that uses small weights that can be lifted from a holder. Their weight force is applied to the thruster table by a thin wire guided over a deflection pulley. While the voice coil method is faster, shows smaller variances and allows a larger number of measurement points compared to the weight calibrator, it may show a systematic error. The gravimetric method verifies the calibration to an absolute standard. Figure 9 pictures the mechanism that is in charge of lifting the small weights. In our setup we use three weights.

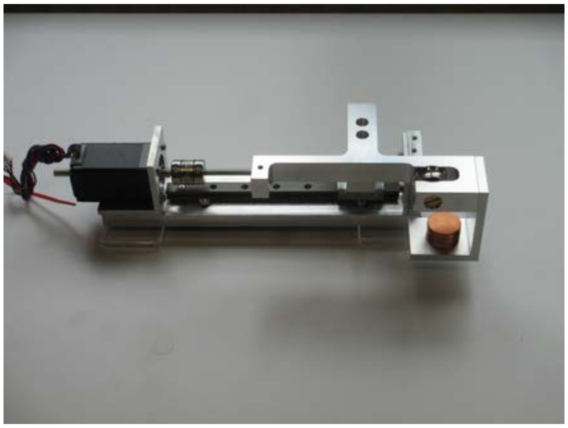

Figure 9. Gravimetric calibration mechanism with three stacked copper weights (cylindrical copper-colored pieces on the right).

Like the Option 1, this calibration can be triggered whenever needed, especially during an experiment. Being able to perform such an online calibration is a very important feature for long term tests where drifts may happen.

The calibration shows an excellent linearity and very low hysteresis. The hysteresis of the balance response depends on the quality of supply lines routed to the table. The transfer function between applied force and signal shows no hysteresis as long as the response follows Hooke's law:

$F = -k \cdot dx$, with a constant stiffness k. Unfortunately, real world materials and parts exhibit non-ideal behavior. Especially cables with plastic material cladding insulation or polymer hoses for water cooling introduce nonlinearities. The effects are worsened if the cable temperature or the hose line pressure varies.

VI. Commissioning Tests

Figure 10 shows the thrust balance with a radiofrequency ion thruster installed in DLR’s test facility. The side covers are not mounted and the cable harp can be seen. Commissioning began with recording simulated thrust steps forced by the calibrated voice coil. Figure 11 shows this test, pulling with steps of 17.2mN, up to about 150mN. This upper limit has been set by the available power supply. The curve shows the slight oscillation with damping at the beginning of a step, and the satisfactory shape. The move into stable conditions is accomplished in well below 30s. The repeatability of large and small thrust steps is shown in Figure 12. In the upper diagram the force had a constant step value of 108 mN, while data using a small step of 17.8 mN applied to the balance is shown in the lower image. As will other oscillating systems, the damping factor is always a compromise between overshooting and longer settling time.

In conclusion, the first part of the commissioning showed a good reproducibility of simulated thrust steps, with a deviation of less than 1%.

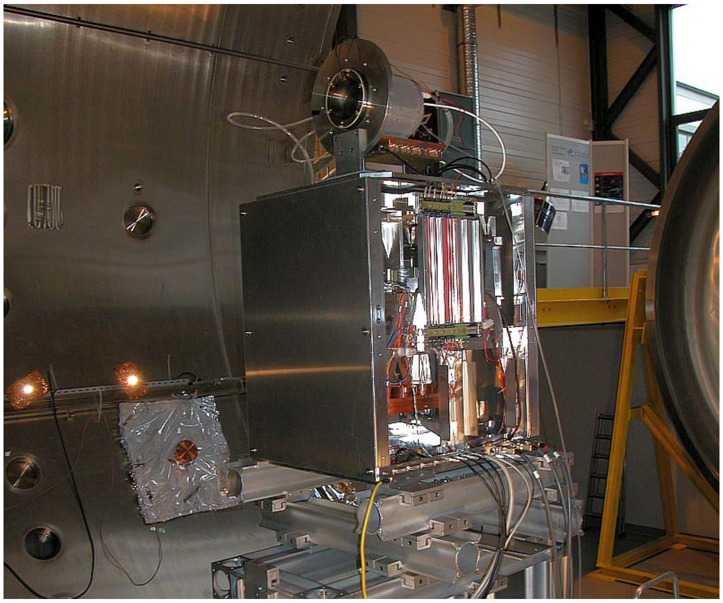

Figure 10. Ion engine mounted on the thrust balance in DLR's vacuum chamber.

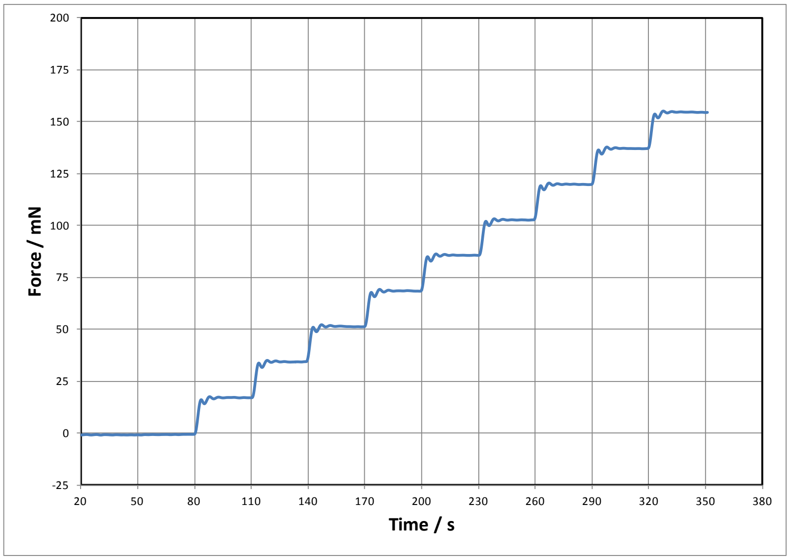

Figure 11. Ramp up with constant step size of 17.2 mN.

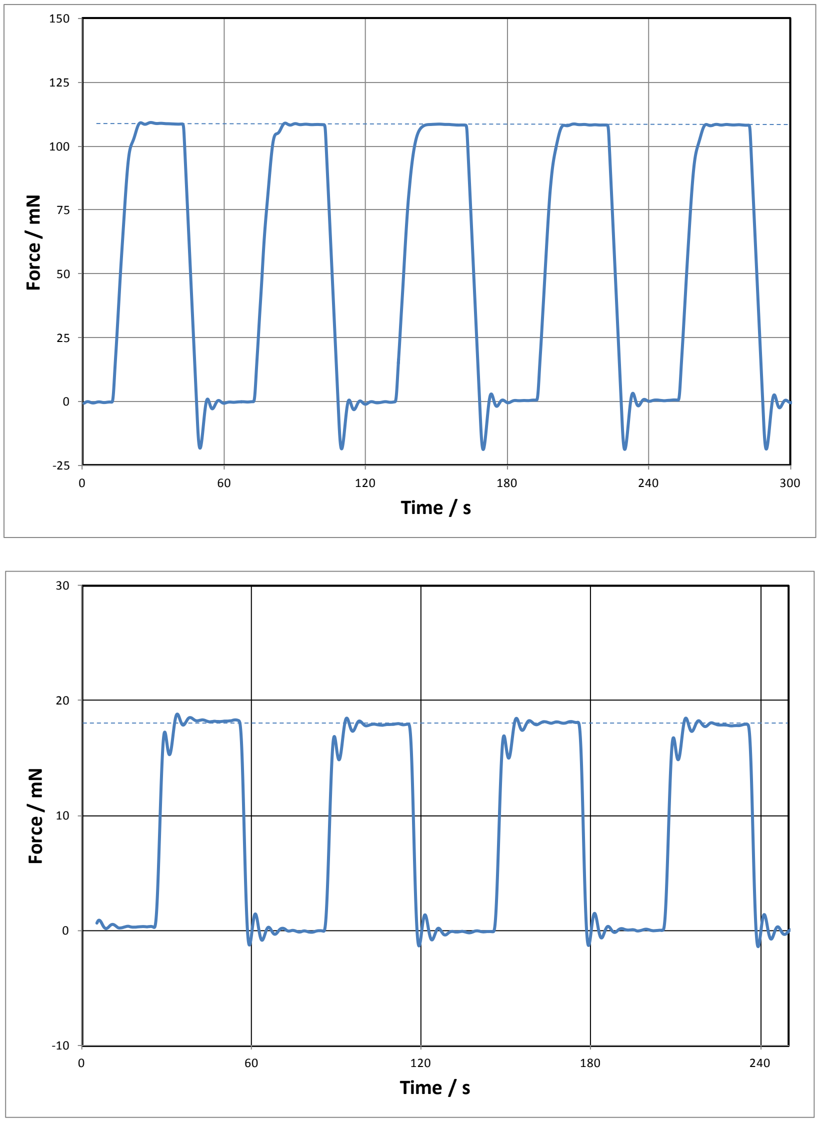

Figure 12. Repeatability demonstration with constant step height (top: 108 mN, bottom: 17.8 mN).

The above tests were performed in ambient air. The damping is even more important in vacuum, as a major part of the friction disappears at low pressure. Additional friction is of course introduced with more cables (e.g. with outer plastic wrapping). This is not an issue, as long as the forces by cables and hoses are linear and constant.

VII. Conclusion

The new balance is now part of the measurement equipment of DLR's electric propulsion test facility STG-ET. The assembly of the balance is almost completed and the device is integrated in the vacuum chamber. The electronics components were sealed for vacuum operation and have been tested with simulated thrust forces by a voice coil. The next step will be the calibration with the gravimetric system.

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