Development of a compact milli-Newton Thrust Balance and Characterization of a miniature Hall-Effect Thruster

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Abstract: A compact torsion spring thrust balance for electric propulsion systems was designed, developed and tested at the advanced propulsion laboratory of the Institute of Aerospace Engineering at the Technical University of Dresden. By measuring the angular deflection of two torsion springs onto which an electric propulsion system is mounted, thrust in the range of 0 - 10 mN with a resolution of ~1 µN can be measured. Measurement range can be adapted to thrust up to one Newton by exchanging torsion springs with different spring rates. The balance is put under vacuum conditions and serves as a testbed to study performance of the TUD-H1-S miniature Hall-effect thruster with a power consumption of 50 W – 150 W in combination with a developed cathode. First thrust measurements and properties of the thrust balance were obtained and will be presented in this paper.

Nomenclature

T	=	period of oscillation
I	=	momentum of inertia of the frame
C	=	torsional spring rate
M	=	momentum at the rotational axis generated by the thruster
φ	=	deflection angle of the frame
Δx	=	measured deflection
l	=	lever arm of the interferometer
F	=	thrust generated by the electric propulsion system
L	=	lever arm of the thrust vector

I.Introduction

ELECTRIC propulsion systems have a continuous rise in popularity due to their ability to operate with comparatively low amounts of propellant and with a long life-time. Converting electrical energy into kinetic energy of ions with high specific impulses to produce thrust is a beneficial way of maneuvering a spacecraft. The electrical energy can be obtained in orbit by solar panels, radioisotope thermoelectric generators or other energy sources, thus creating an advantage in contrast to chemical propulsion systems.

A notable example for a popular and flight proven electric propulsion system is the Hall-effect thruster developed in the 1960s. It converts propellant and electrical power into kinetic energy of ionized gas, thus creating thrust due to conservation of momentum. Among other electric propulsion systems, the Hall-effect thruster is one of the commonly used systems, mainly used for orbit insertions and attitude and orbit control systems of satellites.

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With the purpose to provide propulsion for small satellites as well as to serve as a testbed for a corresponding cathode development[1], we developed the miniature Hall-effect thruster[2] TUD-H1-S (Fig. 1) with a power consumption of 50 W – 150 W. To characterize this system, we will offer a detailed description of a compact torsion balance, onto which the Hall-effect-thruster is being tested to get a detailed look at its performance for further improvements.

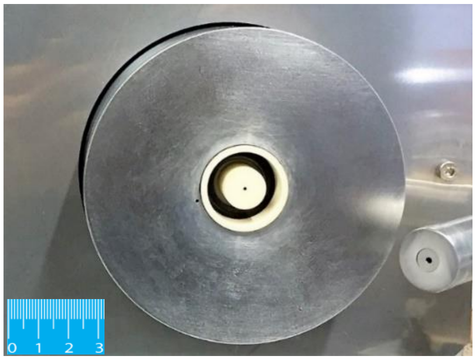

Figure 1. TUD-H1-S. *Miniature Hall-effect thruster developed at the Institute of Aerospace Engineering at TU Dresden.*

The thrust balance is based on two torsion springs which experience a torque due to thrust of the electric propulsion system. Different research facilities developed systems for thrust measurement using the properties of deflecting springs. An example for such a system is a thrust stand developed by Kokal et al. at the department of mechanical engineering in Istanbul, Turkey[3]. Their approach is an inverted pendulum configuration which includes flexural pivots made of small stainless steel-plates. Any thrust provided by the electric propulsion systems leads to a deflection of the frame, thus providing a measurable displacement for calculating thrust in the range of millinewton with a resolution of ~100 µN.

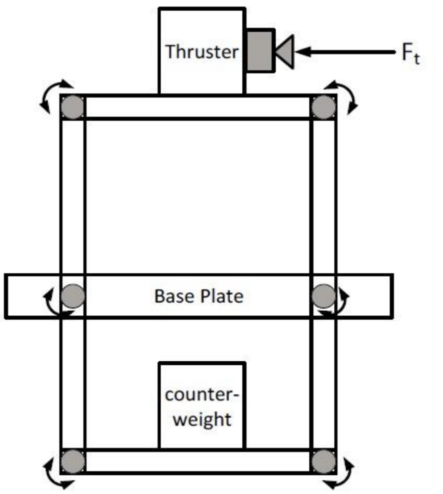

Figure 2. Balanced inverted double-pendulum. *Schematic concept of the thrust stand developed at the electric propulsion test facility at DLR Goettingen*[4].

Another notable example is a balanced inverted double-pendulum thrust stand[4] developed by Neumann et al. at the electric propulsion test facility at DLR Goettingen (Fig. 2), which is capable of thrust measurements up to 250 mN, extendable to 1 N with a resolution of ~250 µN for thruster weights up to 20 kg.

Prior to the completion of our compact torsion balance, thrust measurements of the Hall-effect thruster took place by fixating the thruster inside a vacuum chamber and measure the deflection of a light weight pendulum plate onto which the accelerated ions impacted[5]. This setup provided rough estimations of thrust, but it was not suitable for detailed investigations on thruster performance. The uncertainty of this method of thrust measurement lead to the development of a new thrust balance, where the thruster can be mounted on.

This paper provides a detailed look on the developed thrust balance and its properties, as well as first thrust measurements with the TUD- H1-S Hall-effect thruster.

II.Thrust stand requirements and design

Primary use of the torsion balance is to characterize the TUD-H1-S Hall-effect thruster in conjunction with our developed cathode. The expected thrust of this setup is in the range of few millinewton. To characterize this system in an effective manner, the influence of every parameter available should be investigated. Especially the magnetic field is a parameter, that requires relatively large copper coils, thus accumulating a weight of approximately 3.5 kg for the whole thruster. This determining constraint of high weight lead to a thrust stand design where the influence of gravitational force vector can be separated from the thrust vector. We therefore decided to develop a torsion spring based thrust balance (Fig. 3), where the thrust vector provides a torque on two torsion springs, hence deflecting the whole thruster frame (chapter III, section A).

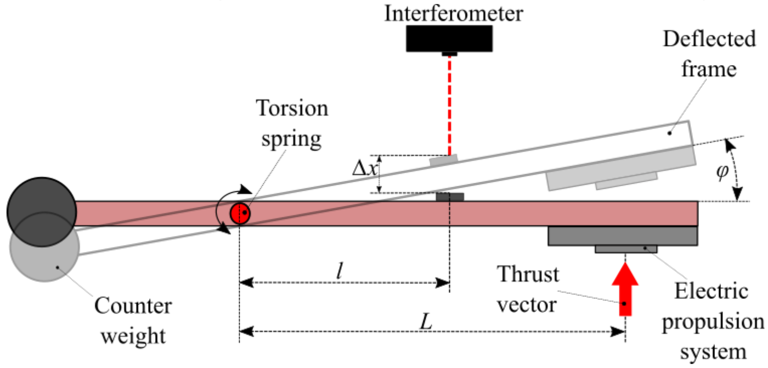

Figure 3. Torsion based measurement principle. *Schematic concept (top view) of the thrust stand developed at the Institute of Aerospace Engineering at TU Dresden*

This deflection can then be measured with an interferometer and converted into a corresponding thrust (chapter III, section B). The torsion springs are designed to withstand substantial amounts of weight in the vertical axis, but they are sensible towards shearing force. This constraint and the relatively high weight of the thruster required the use of counter weights to prevent damage to the springs.

To provide a suitable test environment for propulsion systems, that are designed to operate in space, the balance is constructed to fit into our cryogenic vacuum chamber. The chamber has an inner diameter of 0.5 m, a length of 1 m and a base pressure of 1e-07 mbar. The typical pressure of 1e-04 mbar during measurements is low enough to extract entrapped gases within materials, therefore minimum outgassing materials were used in the design.

The position of the thrust vector is almost centered within the inner diameter of the vacuum chamber to prevent interactions of plasma with the chamber walls.

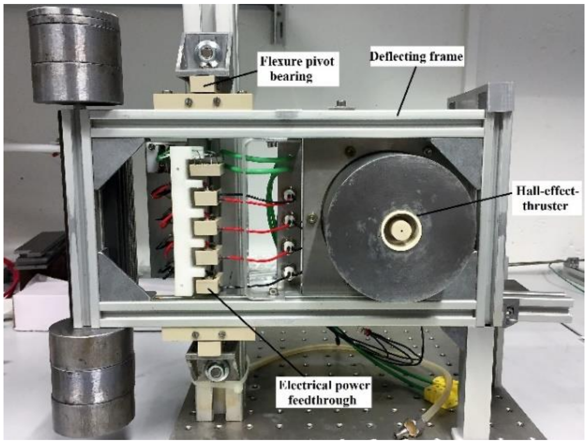

Figure 4. Thrust stand front. *Front view of the thrust stand with the mounted Hall-effect thruster and electrical power feedthroughs.*

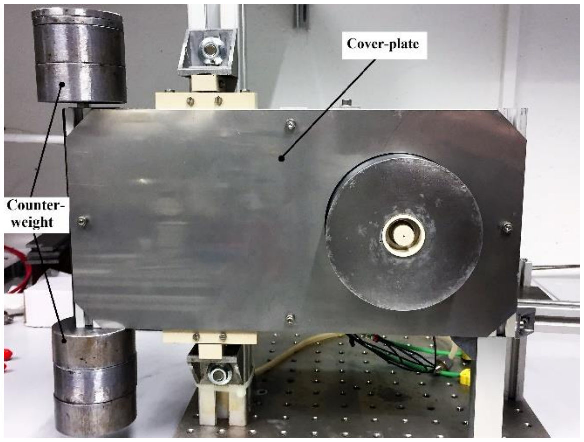

Figure 5. Thrust stand front. *Front view of the thrust balance with a stainless-steel cover-plate to protect sensitive parts from plasma and short circuits.*

The mainframe of the balance structure consists of lightweight aluminum profiles, that can be easily adapted to fit different electric propulsion systems. It is covered by a stainless steel-plate to protect electrical feedthroughs and other sensitive parts from plasma and short circuits (Fig. 5).

The difficulty in measuring thrust in the range of a few millinewton via deflection of a torsion spring is to exclude any kind of disturbing forces on the system. Among others, the main disturbances originate from stiffness of cables and propellant tubes, noise of any kind of moving objects near or inside the vacuum chamber and many more. We have managed to eliminate many of these disturbances to a point, where reliable measurement data can be obtained.

The first task was to eliminate the stiffness of every cable from measurements. To achieve that, we developed a new kind of electrical power feedthrough, using a liquid metal and coaxial cables (chapter III, section D). This feedthrough utilizes easily accessible interfaces with BNC connectors and thermocouple connectors (Fig. 6). Additionally, we designed an eddy current damping system to eliminate most of the motion noise to a point, where resolution of thrust measurement reached ~1 µN (chapter III, section C).

The rotating frame, including propulsion system, electrical power feedthroughs, BNC interface (B) and counter weights is supported by a single aluminum profile, which is bolted into an aluminum breadboard. This breadboard is positioned on top of rubber pads, that are fixed onto aluminum beams inside the vacuum chamber.

For the operation of the Hall-effect thruster, argon was used as propellant, delivered by two *Brooks Instruments GF40* mass flow controllers, each of which with a mass flow rate of up to 400 ml/min. Two flexible silicone tubes are available to connect with the thrust balance and vacuum chamber feedthroughs.

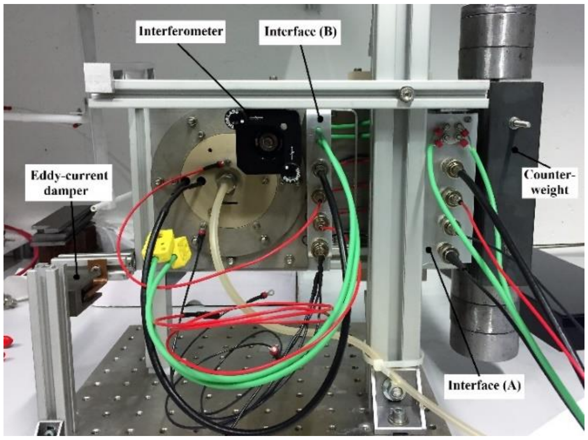

Figure 6. Thrust stand back. *Rear view of thrust stand with connected cables and fixed to the breadboard.*

III.Thrust stand components

A. Flexure pivot bearing

The most important parts of the balance are the flexure torsion springs. These torsion springs are flexure based bearings, utilizing internal flat crossed springs, that are capsuled in a cylindrical housing to provide precise rotation with low hysteresis and no frictional losses. They are clamped into PEEK mounts and aligned vertically with each other equidistant to the thrust vector of the electric propulsion system which is about to be measured.

Currently there are three distinct kinds of springs that can be clamped into the PEEK mounts, leading to three possible ranges of thrust measurement:

1) 0 – 10 mN
2) 0 – 250 mN
3) 0 – 1 N

To detect possible failure currents in the system, the electric potential of the main frame and the vacuum chamber had to be isolated. Therefore, PEEK was the material of choice for the bearing mounts. It has an excellent combination of properties to isolate the electric potentials and to be durable enough to withstand the weight of the whole frame.

The torsion springs have already been used in prior projects[6,7], hence the performance could be slightly different from the data sheet. The task before first measurements was to analyze and calibrate the torsional spring rate to compensate the loss in performance (chapter IV, section A).

The detection of failure currents can be enabled by applying a bias voltage onto the isolated thruster frame and observe any changes during thrust measurements.

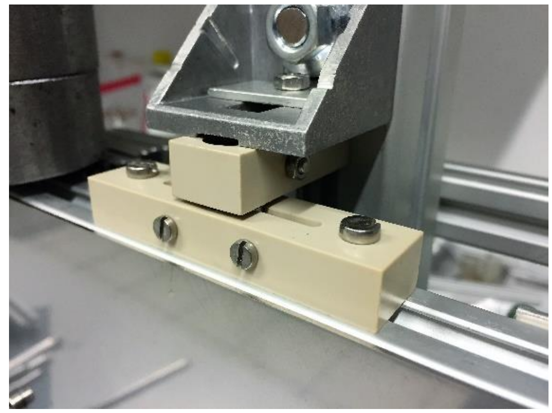

Figure 7. PEEK housing. *Torsion springs are clamped into two separate PEEK components and fixated at aluminum profiles.*

B. Displacement sensor

Another important part of being able to measure thrust with a resolution of µN through deflection is the performance of the distance measuring device. System of choice was the interferometer *IDS3010* by *Attocube* with the *M15.5/C1.6/FLEX* sensor head and a resolution of one picometer at a work distance of up to 5 m. Counterpart and laser target is a small mirror, that is mounted onto the thruster frame and aligned with the interferometer as seen in Fig. 8. Hence, creating a setup, that is able to provide an excellent resolution for the measurement of small displacements.

Due to the fact, that the torsion balance is rotating, thus changing angle of the reflecting laser, the maximum range of thrust measurement is determined by the maximum deflection angle of the interferometer.

It is the combination of interferometer lever arm l, thrust vector lever arm L and spring stiffness, that sets the measurement limits of each configuration. These parameters can easily be modified to create setups for different propulsion systems and thrust ranges.

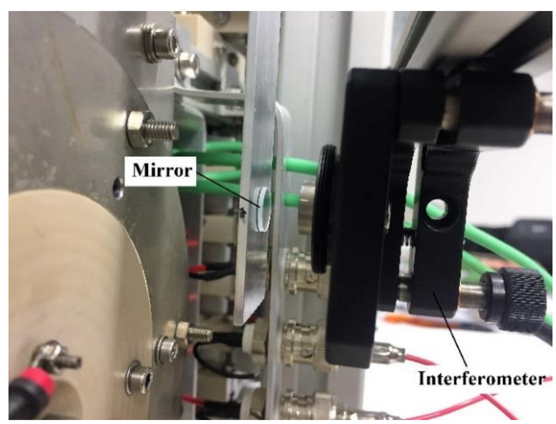

Figure 8. Displacement sensor. *Interferometer aligned with mirror.*

C. Damping system

To decrease the influence of motion noise in the position measurement, we implemented a passive damping system utilizing so-called eddy currents. The Movement of people walking near the vacuum chamber has a significant impact on noise level as well as the cryogenic pump of the chamber due to continuous motion of the cooling process.

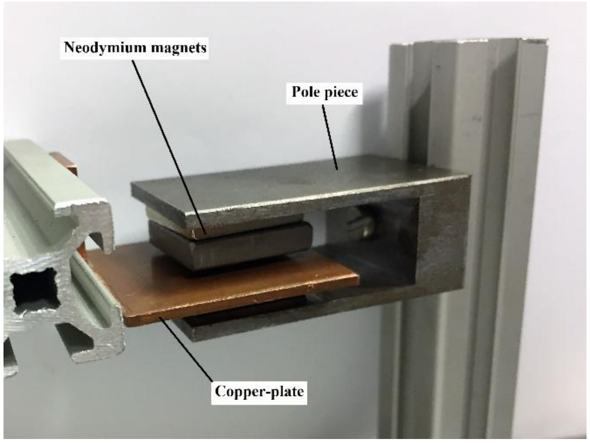

Figure 9. Damping system. *Eddy-current based damper with copper plate, carbon steel pole piece and N45 neodymium magnets*

Designing the thrust balance in a way, that any thrust deflects the mounting frame only in the horizontal plane, leads to a high insensitiveness towards vertical motion noise. Hence, leaving us with one remaining degree of freedom in the horizontal plane, that must be taken care of by a damping system.

The system of choice consists of a U-shaped carbon steel element, which is fixed to the aluminum breadboard and has the purpose to direct the magnetic field lines provided by two strong quadratic shaped N45 neodymium permanent magnets (Fig. 9). This design leads to a homogenous magnetic field in the remaining gap between the two magnets. A copper plate is penetrated by the strong magnetic field and mounted to the deflecting frame. If the pole piece and the copper plate are at rest with respect to each other, this system has no influence at the measurement whatsoever. Any deflections of the frame lead to electrical currents, that are induced into the copper plate perpendicular to the magnetic field lines of the permanent magnet due to Faraday`s law of induction. These eddy-currents lead to damping forces, counteracting unwanted movements of the thruster frame and result in a reliable damping system.

The performance of the installed damper is presented in Fig. 10. By applying an initial deflection amplitude of 400 µm – 600 µm, an oscillation of the thruster frame can be observed. The active eddy-current damper decreases magnitude of oscillating amplitudes to keep the level of noise as low as possible. Oscillations would not decay for several hours otherwise.

In addition to the damping of motion with eddy-currents, we positioned the thrust stand breadboard onto rubber pads, that are fixated to aluminum beams inside the vacuum chamber. These pads were added to isolate the thrust balance from the general noise level of the vacuum chamber, that originated from the cryogenic pump.

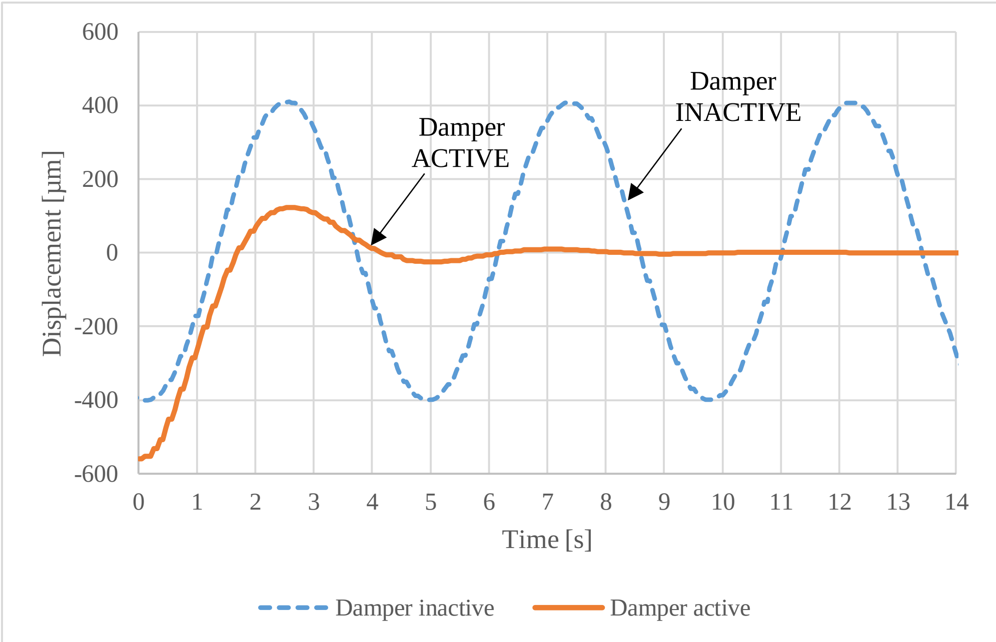

Figure 10. Displacement measurement. *Deflection oscillation due to initial manual displacement to characterize the eddy-current damper performance compared with a non-damped system.*

D. Electrical power supply

Measuring the deflection of the balance frame as a result of thrust is very sensible towards any kind of stiff connections to the mounting frame. Every connected cable from the power supplies to the propulsion system disturbs measurements by preventing small deflection amplitudes due to stiffness of the cable material. Furthermore, electrostatic fields produced by currents flowing through the cables could interact with each other and the thrust stand. This could lead to the deflection of the balance frame, which results in the measurement of a pseudo-thrust.

To counteract this problem, we developed an electrical power feedthrough using coaxial cables and a metal alloy called Galinstan, which is liquid at room temperature (Fig 11).

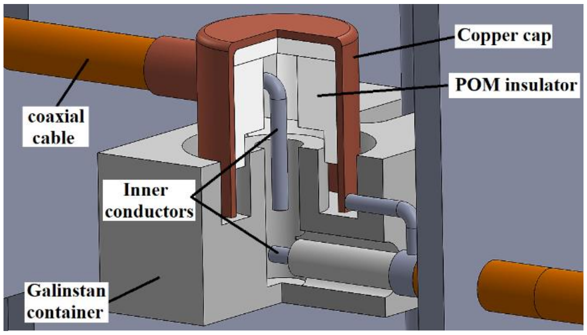

Figure 11. Single electrical feedthrough. *Sectional view of the Galinstan container and coaxial contacts.*

We designed the external connections in such a way, that they are easily exchangeable and adaptable to various kinds of electric propulsion systems. The design involves the usage of two interfaces as seen in Fig. 12. Interface (A) on the right is fixed to the thrust balance base and offers BNC connectors for coaxial cable contacts from the vacuum chamber feedthrough as well as thermocouple connectors. Any cable connected to interface (A) is not interfering the thrust measurement whatsoever. The Interface on the left (B) is mounted to the deflecting frame and offers connections to thruster, cathode and thermoelements. The challenging part was the design of the connection between interface (A) and (B) in such a way, that it does not disturb the deflection. We therefore developed a liquid metal electrical feedthrough as seen in Fig. 13. The shields of the coaxial cables originating from BNC connectors at interface (A) are soldered to copper caps, as seen in Fig. 11. The inner conductor is separated from the copper by POM inserts inside the cap. These connectors are then placed in the rotational axis of the thrust balance and submerged in the liquid metal inside the PEEK housings. The only remaining mechanical interaction between the two interfaces is the liquid friction originating from the rotating copper caps inside the Galinstan during deflection of the balance frame. As a consequence of the position in the rotational axis, this liquid friction is reduced to a minimum due to the small lever arm of the copper caps upon which the friction moment scales. Thus, creating an electric power feedthrough which is independent of cable stiffness. To increase the number of connections, these Galinstan-based feedthroughs must be positioned above each other in the rotational axis.

For the power supply of the Hall-effect thruster as well as the cathode, we used two *Delta Elektronika SM660-AR-11*, each of which delivering up to 660 V and 11 A at a maximum of 3.3 kW. The copper coil for the magnetic field and the bias on the thruster frame were connected to a *Rigol DP832A* with the capability of 30 V and 3 A at maximum of 90 W.

The copper caps have not been installed yet for first thrust measurements, instead the coaxial cables between the two interfaces were replaced by single core cables.

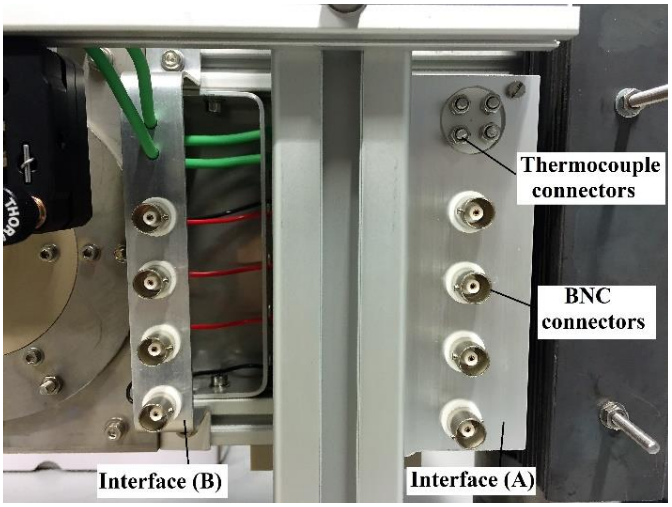

Figure 12. Electrical Interfaces. *Fixed Interface (A) on the right; Freely rotating interface (B) on the left, mounted to the thruster frame.*

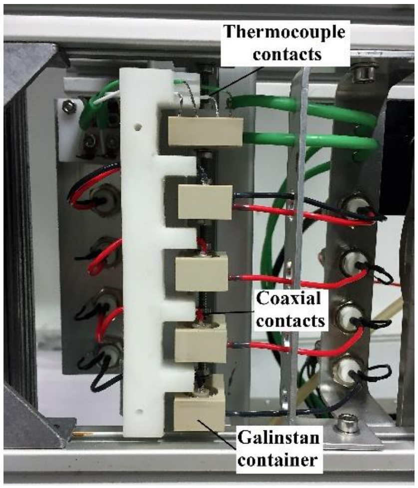

Figure 13. Electrical power feedthrough. *Liquid metal container with coaxial and thermocouple contacts positioned in the rotational axis of the thruster frame*

IV.Calibration and thrust measurement

A. Calibration process

To receive reasonable data from thrust measurements, a calibration of the system had to be done. Due to the fact, that the thrust is not directly measured, but calculated from the deflection of the torsional spring, we had to perform a sufficiently accurate determination of the torsional spring rate. To achieve this, the whole setup including thrust stand and thruster was placed into the vacuum chamber and connected to the non-operational power supplies. By manual displacement and release of the thruster frame without the eddy current damper, the system oscillated depending on the initial displacement amplitude. This oscillation was then analyzed regarding periodic time T and moment of inertia I of the thruster frame computed via a 3D-CAD model. To calculate the torsional spring rate, the following equation for periodic time of a harmonic oscillator was used:

$$T = 2\pi\sqrt{\frac{I}{C}} \qquad (1)$$

Utilizing the analyzed data of the undamped oscillation for Eq. (1) indicates the torsional spring rate C as the only remaining parameter. To finish the calibration process, Eq. (1) is rearranged to obtain the torsional spring rate C.

It is important to mention, that the calibration took place at atmospheric pressure, thus leaving a tiny damping force due to aerodynamic resistance of the oscillating frame.

B. Thrust measurement

The calibrated thrust stand is placed under vacuum conditions in the range of 1e-7mbar environmental pressure and the electric propulsion system is put into operational mode. Given that the thrust is not directly measured, but calculated through distance measurement, we devised equations to convert these values. Originating from the geometric properties of the thrust balance, we used the following three equations:

$$\sin(\varphi) = \frac{\Delta x}{l} \qquad (2)$$

$$M = 2C\varphi \qquad (3)$$

$$F = \frac{M}{L} \qquad (4)$$

Eq. (2) is based on the emerging triangle between the resting and the deflecting frame (Fig. 14). Including the measured distance Δx provided by the interferometer at the lever arm l, the deflection angle φ of the thruster frame can be obtained. The resulting moment M at the two torsion springs, each of which equidistant to the thrust vector, is then calculated with Eq. (3) and (2) in combination with the calculated spring rate C from section A. Finally, thrust can be obtained by using Eq. (4) and the calculated value from Eq. (3), including the lever arm L of the thrust vector.

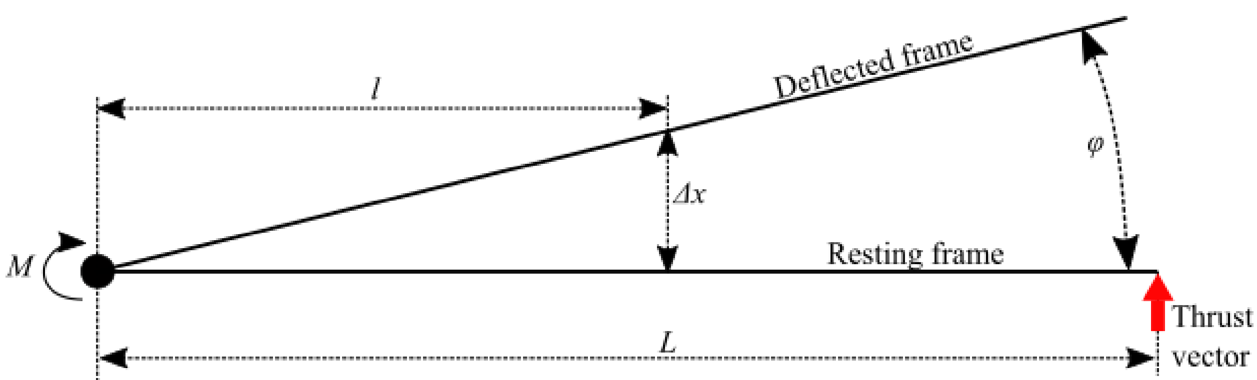

Figure 14. Measurement parameters. *Schematic sketch of the parameters used in Eq. (2)-(4), originating from the geometric properties of the thrust balance.*

V. Hall-effect thruster operation

In this section, we will describe a typical ignition process of the Hall-effect thruster as well as received data.

The main purpose of the thrust balance is to evaluate the performance of the TUD-H1-S Hall-effect thruster developed at the TU Dresden in combination with a C12A7 electride hollow cathode. For first tests, we decided to exchange our developed cathode with a *SHCD1000* hollow cathode by *Kaufman&Robinson Inc.* to concentrate on analyzing the thruster primarily.

The thrust balance including Hall-effect thruster and hollow cathode is put under vacuum conditions. As a first task argon flow through the cathode is enabled by the mass flow controllers to eliminate contaminations of unwanted residual gases. Proceeding with an applied keeper voltage of 600V and a keeper current of 3A, the cathode is put into operational mode.

Parameter	Value
Power consumption	178 W
Anode voltage	58 V
Anode current	3 A
Keeper voltage	23 V
Keeper current	1 A
Argon mass flow	400 ml/min
Coil current	0.4 A
Magnetic field	80 G

Figure 15. Hall-effect thruster parameters. *Chart with parameters from the TUD-H1-S during maximum thrust of 1.5 mN*

After the successful ignition of the cathode, we decrease the keeper current to 1 A until the operational temperature is reached. By enabling a coil current of 0.4 A, a magnetic field is established. According to Nürmberger et al. [5] the magnetic field strength with the parameters mentioned, results in ~80 Gauss. This field forces electrons provided by the cathode into a circular trajectory inside the ionization zone as soon as anode voltage is applied. To start the Hall-effect thruster, we had to regulate the argon mass flow through the thruster to 400 ml/min and apply an anode current of 3A at 600V anode voltage. Once the thruster is in operational mode, parameters can be adjusted to observe changes in thrust.

To evaluate the general compatibility and behavior of the Hall-effect thruster in combination with the newly developed torsion spring thrust balance, we performed a two-hour operational test of the thruster without a measurement of thrust (Fig. 16).

First thrust measurements were obtained by three thruster ignition processes, each of which with a period of about 100 seconds (Fig. 17). The plot shows calculated thrust over time with a noise of ~20 µN reaching a maximum thrust of 1.5 mN for the TUD-H1-S thruster. The measurement indicated a low ratio of thrust provided by the accelerated ions in comparison to the argon mass flow as seen in the first operational period of the thruster in Fig. 17. Additionally, the high amount of noise and the large deflection amplitudes are due to an earlier version of damping system, that was not as effective as the latest version, which reduced the noise to ~1 µN.

It is important to mention, that the different peaks in thrust, shown in Fig. 17 originated from modifying the available parameters, that are not shown in the plot. For a maximum thrust of 1.5 mN during the first ignition process, the Hall-effect thruster operated with the parameters shown in Fig. 15.

Evaluations of the first thrust measurement data lead to the conclusion, that magnitude of the specific impulse is low due to the thruster depending on an argon mass flow 400 ml/min. Considering ionization rate, efficiency and other properties have shown, that performance of the TUD-H1-S Hall-effect thruster leaves room for improvements.

Due to problems with the hollow cathode, further thrust measurements were delayed.

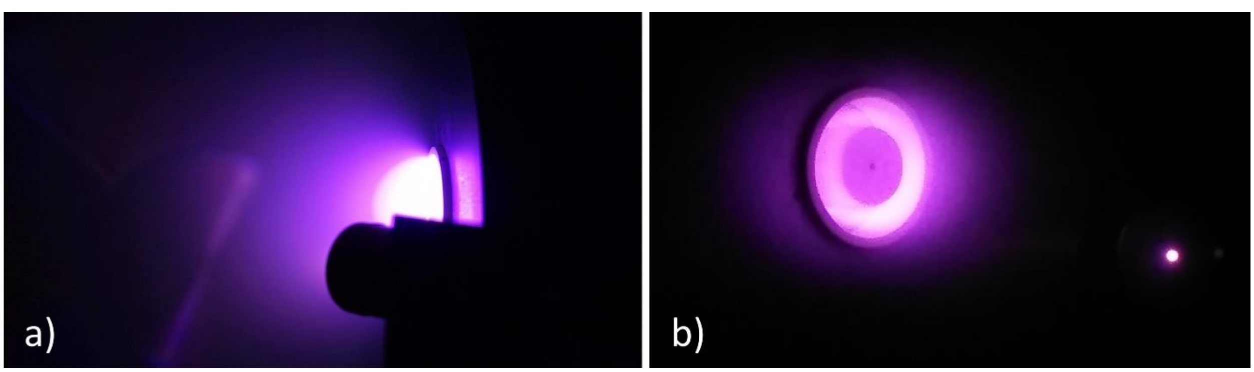

Figure 16. Hall-effect thruster TUD-H1-S in operation. *Side view (a) and front view (b) during the two-hour operating session.*

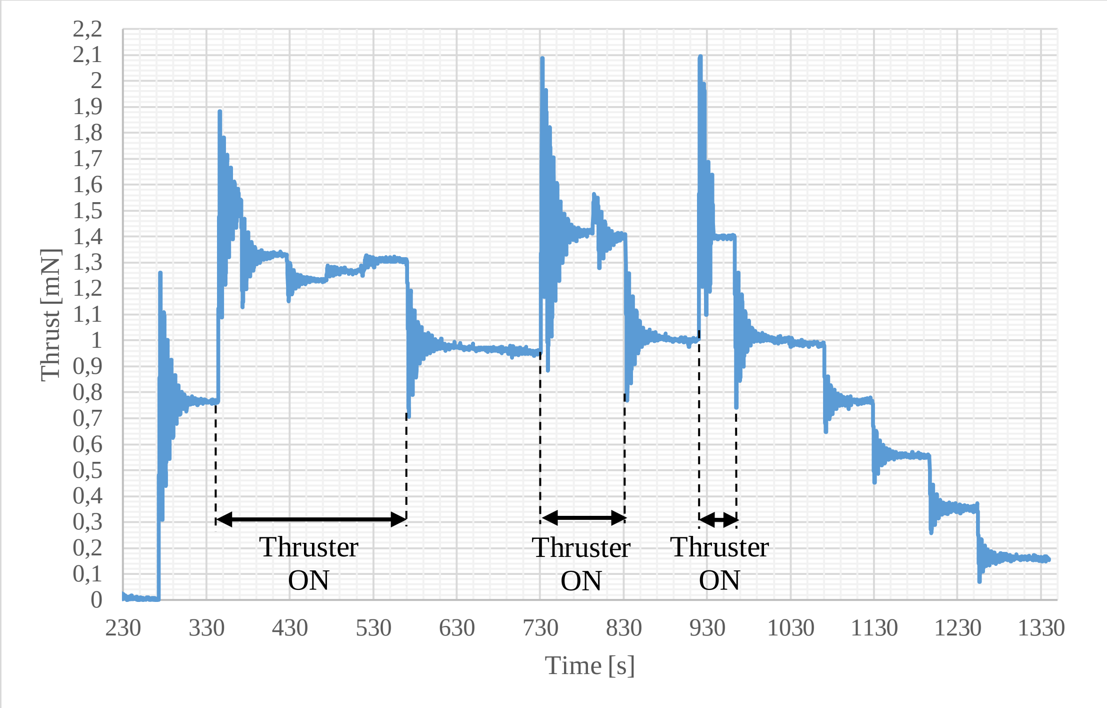

Figure 17. Thrust measurement diagram. *First measurement of the TUD-H1-S Hall-effect thruster with modified parameters over time.*

VI.Conclusion and further work

A compact torsion balance was developed and successfully tested in the advanced propulsion laboratory of the Institute of Aerospace Engineering at TU Dresden. Thrust measurements in the range of up to 10 mN with a noise of ~1 µN are possible. This range is extendable to 250 mN and up to 1 N, each of which are not characterized in terms of noise yet. Due to the adaptable design, a wide variety of electric propulsion systems can be characterized. A new way of electric power feedthrough as well as measurement techniques were presented.

First thrust measurements of the TUD-H1-S Hall-effect thruster have been obtained to get a look at its performance. Due to problems with the cathode, no extended thrust measurements could be realized.

Modifying the current calibration technique of torsion springs is the first task for improvements. The method of analyzing amplitude and oscillation period of the frame by manual deflection and calculating the spring constant will be extended by installing a linear voice coil. This system can be used to verify the calculated torsional spring rate and improve thrust measurements. In addition, this kind of calibration can be performed under vacuum conditions, eliminating the damping effect of aerodynamic resistance during oscillations.

A profound influence on the thrust measurements to date is the level of noise originating from the cryogenic pump. Comparing the noise in operation of the cold head and after disabling it, the level of noise is reduced by at least a factor of ten. Therefore, significant effort has to be taken, to reduce this effect during measurements.

The functionality of the thrust balance was confirmed and improvements for the operation with the TUD-H1-S are not yet required, since the noise level is at least two orders of magnitude below the expected thrust delivered by the Hall-effect thruster. Nevertheless, the measurements indicated a low ratio of thrust provided by the accelerated ions in comparison to the argon mass flow. We therefore have to take the performed characterizations as a basis for a detailed optimization of the Hall-effect thruster.

VII.References

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