

Low Drift Thrust Balance with High Resolution

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Abstract: In this paper we present a small thrust balance for thrusters up to 2 kg developed by AST Advanced Space Technologies GmbH in cooperation with Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR). The measurement range is optimized for 0.1 mN to 250 mN while the full range is up to 1 N. In high dynamic mode the balance is able to resolve a pulsed force of 100 mN with a duration of 100 ms at a repetition rate of 1 Hz. By design the thrust balance is very insensitive to external disturbances. This leads to a very low long term drift which could be demonstrated to be smaller than $\pm 250 \mu\text{N}$ over 27 hours within a non-vacuum laboratory environment with only rudimentary decoupling from external influences.

Nomenclature

<i>AST</i>	= Advanced Space Technologies GmbH
<i>DLR</i>	= Deutsches Zentrum für Luft- und Raumfahrt e.V.
<i>FFT</i>	= Fast Fourier Transform
I_{SP}	= Specific Impulse
<i>NGGM</i>	= Next Generation Gravity Mission
<i>PID</i>	= Proportional-Integral-Derivative
<i>STG – CT</i>	= Simulationsanlage für Treibstrahlen Göttingen - chemische Triebwerke
<i>STG – MT</i>	= Simulationsanlage für Treibstrahlen Göttingen - Mikrotriebwerke

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I. Introduction

AST Advanced Space Technologies GmbH in cooperation with Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) developed a small thrust balance for thrusters with a mass of up to 2 kg. Its operation under vacuum conditions has already successfully been demonstrated during thruster measurement campaigns at DLR. The balance is now part of the standard equipment at the DLR site in Göttingen and it is designated to become integrated into the STG-CT test facility.

In this paper we report test results obtained by measurements at AST which show the capabilities of the thrust balance in its present state.

II. Thrust Balance Design

The AST thrust balance is of the counter balanced, displacement compensated type using a fast voice coil actuator for force compensation. All mechanical and key electronic components were designed by AST and have been improved during several development cycles.

The balance has a measuring capability from 0.1 mN to 1000 mN. By design it is optimized to show best performance in the thrust range from 1 mN to 250 mN.

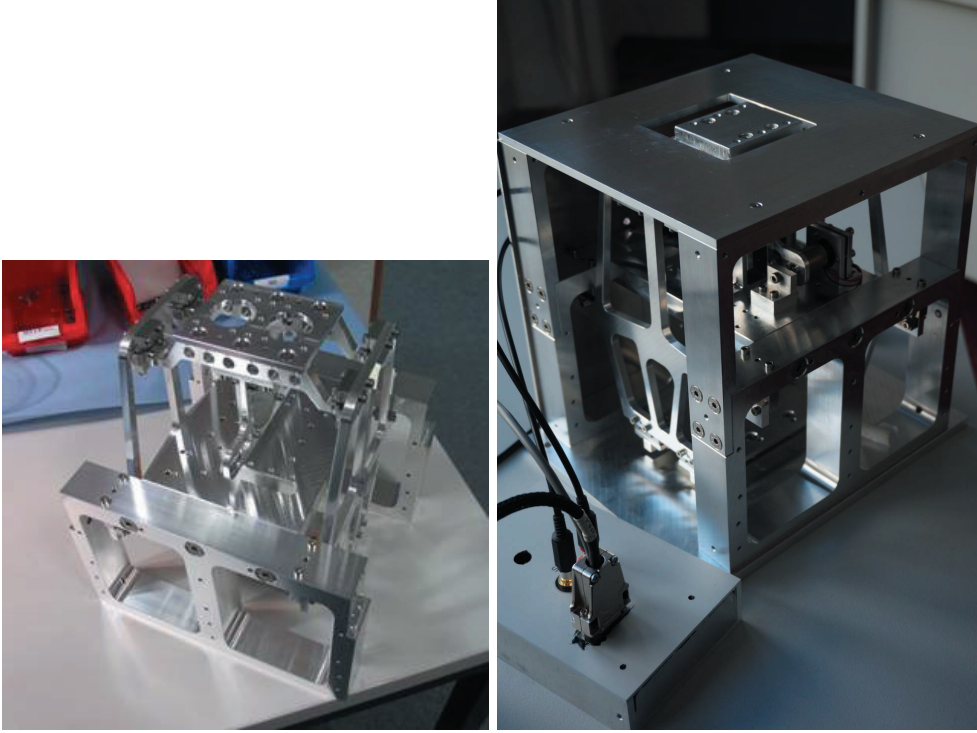


Figure 1. AST thrust balance during assembly (left picture) and in its finished state at DLR (right picture).

The structure of the balance which is based on a parallelogram pendulum is shown in Fig. 1. Due to the particular mechanical design it is highly insensitive to external disturbances. Hence, for most measurement applications there is no need for vibration damping tables etc. Its low sensitivity to environmental influences is also one of the reasons why the thrust balance shows very low drift over time which allows for long term measurement without the need for intermediate offset compensation.

The displacement of the balance is detected by a capacitive sensor and actively compensated by closed-loop PID control. By choosing appropriate parameters the thrust balance can be configured for fast-response as well as for low-noise/high-precision measurement.

III. In-situ Calibration Capability

Besides the voice coil actuator used for active force compensation there is a second identical one for the purpose of in-situ calibration. It provides the ability to apply an arbitrary test force to the thrust balance at any time without generating additional disturbances.

In Fig. 2 the measured signal for a series of equidistant (simulated) thrust levels generated by the second voice coil actuator is shown. Such measurements can be performed at any time to verify the linearity of the balance.

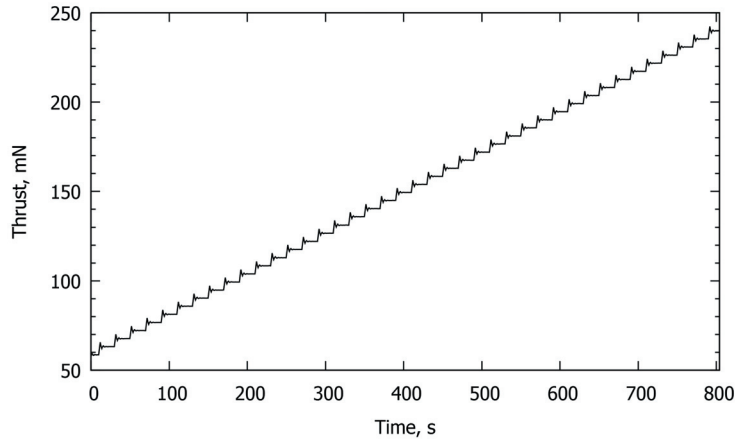


Figure 2. Recorded thrust signal in response to equidistant force levels generated by the second voice coil actuator. This type of calibration measurement can be used to directly verify the systems linearity.

Prior to integration into the thrust balance the proportionality constants for the conversion from coil current to resulting force were determined on a micro scale for both voice coil actuators. The second voice coil actuator can be used to check for any deviation in the ratio of these constants which would indicate a malfunction of the thrust balance or a drift over time (aging). The later will become detected because the second voice coil actuator is not used in normal operation which means it is less affected by aging than its counterpart.

IV. Performance

The data presented in the following sections was obtained during tests at AST under ambient conditions. The thrust balance had been placed on top of a standard laboratory table without any special precautions in respect of decoupling from external disturbances except for a plastic box used as a cover to reduce interaction with air movement. The different test forces were applied via the second voice coil actuator.

A. High Sensitivity Measurement

1. Small Signal Response

Figure 3 shows the measured thrust as response to a test force alternating between 0 and 10 mN. The data was recorded in one shot without any intermediate offset compensation.

There is some overshoot (undershoot, respectively) in the thrust signal each time the applied force changes in magnitude. This is due to the high precision measurement mode where the control loop operates at a limited bandwidth in order to reduce the noise floor.

At each force plateau the stability of the recorded signal is by far better than 0.1 mN which is $< 1\%$ of the measured thrust level. This also holds for the reproducibility between individual measurements as well as for the overall drift.

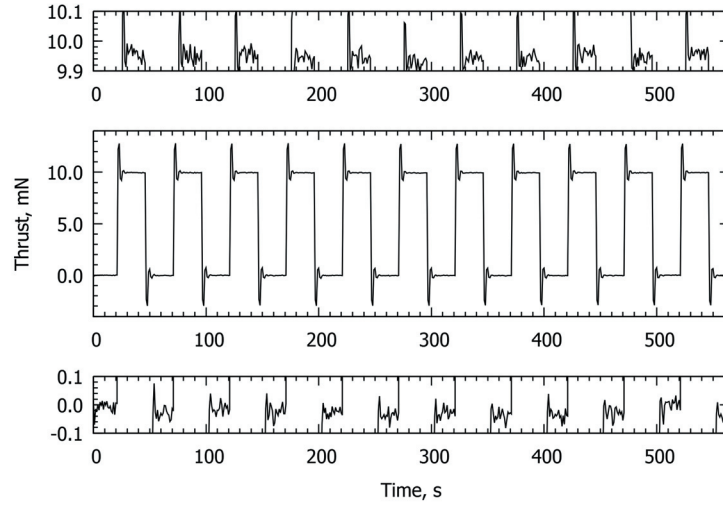


Figure 3. Signal response to a force alternating between 0 and 10 mN.

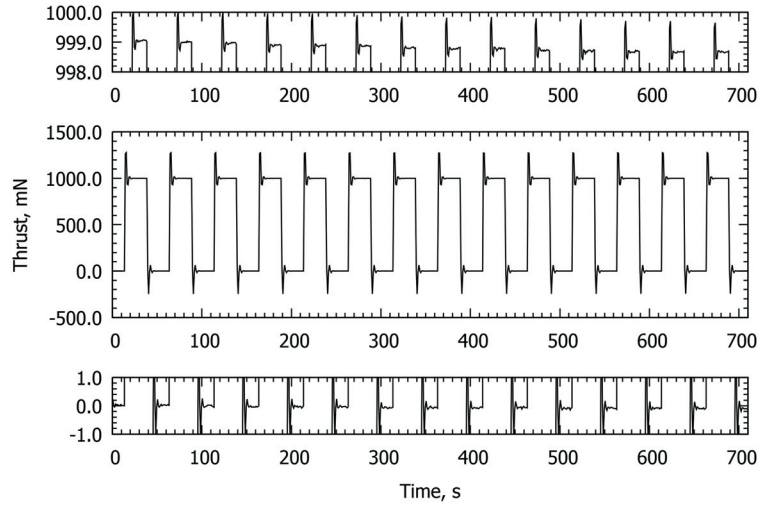


Figure 4. Signal response to a force alternating between 0 and 1000 mN.

2. Large Signal Response

An example for the response to large thrust signals is shown in Fig. 4. The applied force alters between 0 and 1 N which is the upper limit of the thrust balances extended measurement capability. There was no intermediate offset compensation. The deviation between corresponding thrust plateaus as well as the overall drift for the complete measurement add up to less than 0.5 mN which translates to $< 0.05\%$ of the measured thrust level.

B. Fast Response Measurement

Figure 5 shows the response of the balance to rectangular shaped thrust pulses with a magnitude of 100 mN generated by a the second voice coil actuator. The duration of each pulse is 100 ms and the repetition rate is 1 Hz.

In order to achieve fast response the thrust balance was set to high dynamic mode by increasing its bandwidth in software. Therefore, the high dynamic mode shows more noise compared to the high sensitivity setup. However, the main contribution to the signal noise in Fig. 5 is not random but highly reproduced at each individual thrust pulse.

From the close-up of a rising signal edge as shown in Fig. 6 the time constant for measurements in high dynamic mode can be determined to be in the order of 10 ms.

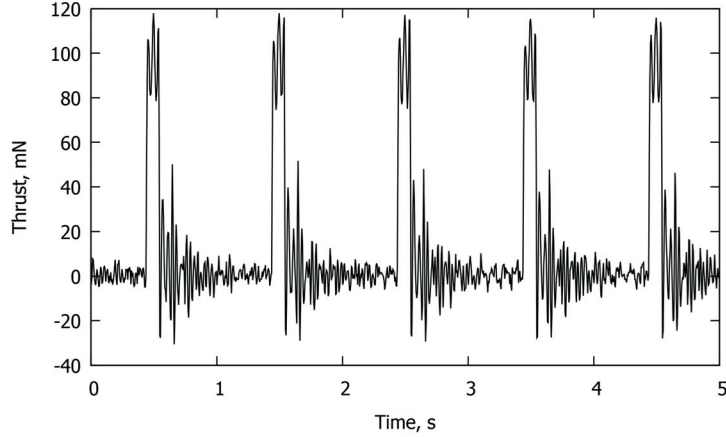


Figure 5. Recorded response to rectangular force pulses of 100 mN with a duration of 100 ms at a repetition rate of 1 Hz.

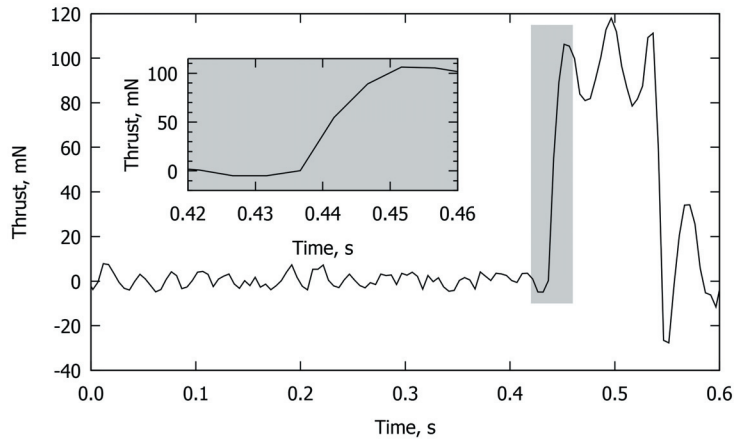


Figure 6. Close-up of the rising edge of the first pulse shown in Fig. 5.

C. Noise Floor Measurement

Long duration measurements have been carried out in order to determine the measurement noise floor. A thrust signal recorded over a time period of 27 hours is shown in Fig. 7. During measurement a sinusoidal pilot tone with a frequency of 25 mHz and an amplitude of 40 μ N (shown in the inset of Fig. 7) was generated by the second voice coil actuator for reference.

The overall signal drift stays within the limits of $\pm 250 \mu$ N for the complete measurement period. With

the balances nominal operational range from 0 to 250 mN as a reference frame this translates to a drift which is less than $\pm 0.1\%$ of the full scale reading over 27 hours.

The main contribution to drift is correlated to the change in room temperature which has an influence on the balance due to poor decoupling from the environment during the test. Therefore the drift could be further reduced by a better isolation from external disturbances.

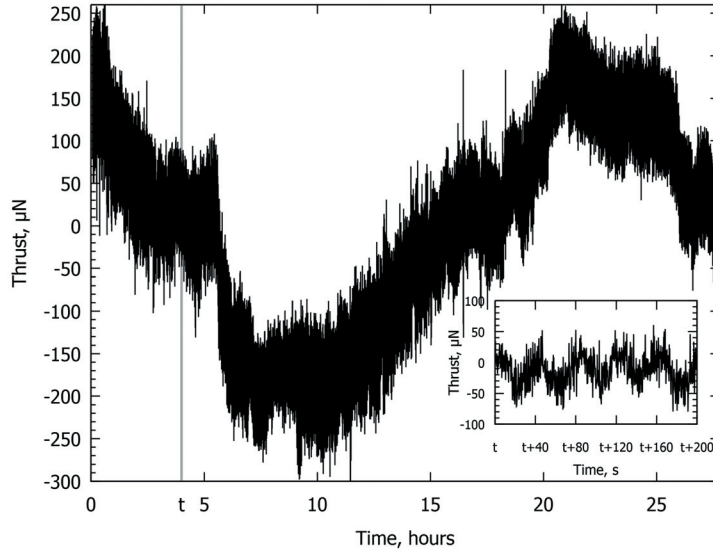


Figure 7. Thrust signal recorded over a period of 27 hours in order to estimate drift/noise. For reference the signal is modulated by a sinusoidal pilot tone with an amplitude of 40 μN at a frequency of 25 mHz.

The calculated thrust noise density is shown in Fig. 8. It has been derived from the measured data by performing a fast Fourier transform (FFT) on the autocorrelation of the signal and taking the square root of the result to end up with units of $\mu\text{N}/\sqrt{\text{Hz}}$.

Besides the thrust noise density of the balance itself with the pilot tone visible at 25 mHz there are two additional curves plotted in Fig. 8 for comparison. These curves mark two different thrust noise requirements of NGGM (Next Generation Gravity Mission)¹.

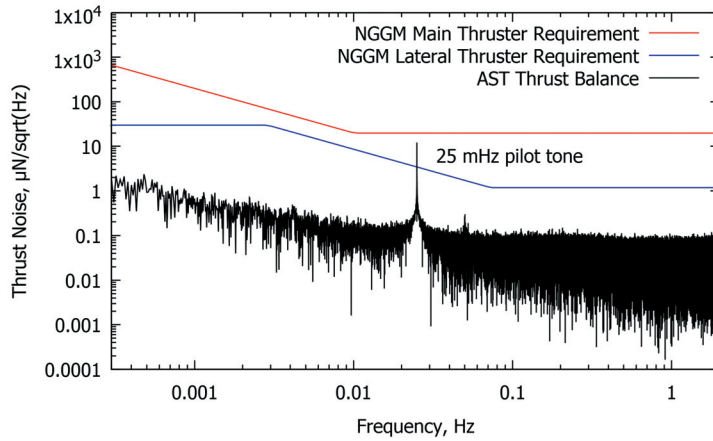


Figure 8. Thrust noise density derived from the measured data shown in Fig. 7. The signal at 25 mHz corresponds to the pilot tone. Thruster requirements for NGGM (Next Generation Gravity Mission) are shown for comparison (data taken from¹).

V. First Measurement Application

One of the first real-world applications for the thrust balance was the determination of the specific impulse I_{SP} of a cold gas thruster manufactured by AST. This test has been performed within the STG-MT test facility at the DLR test site in Göttingen.

The test setup is shown in Fig. 9. The thruster was mounted on the thrust balance within the vacuum

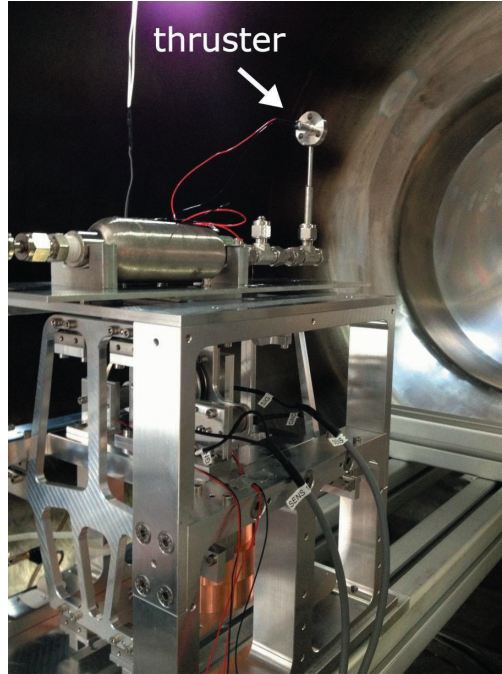


Figure 9. Test setup for determining the specific impulse of a cold gas thruster manufactured by AST. The test was performed within the vacuum chamber of the STG-MT test facility at the DLR site in Göttingen.

chamber of the STG-MT. The nitrogen for the thruster was supplied through a flexible tube (not shown in Fig. 9). The nitrogen pressure at the inlet of the thruster was adjusted to a constant level of 1.5 bar(a) during firing. The resulting mass flow measured was 2960 sccm which translates to 61.6 mg/s.

The thrust signal during one firing of the thruster is shown in Fig. 10. This test was repeated for several

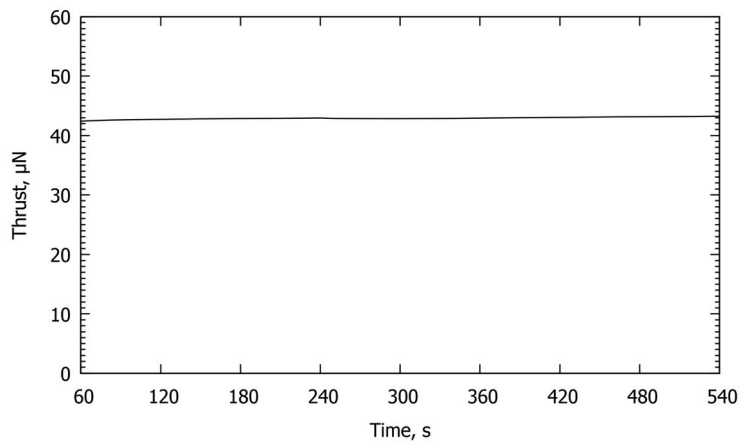


Figure 10. Thrust signal during one firing of the cold gas thruster.

times with the thruster switched off in between the individual firings to allow the thrust to go back to zero.

In table 1 the thrust levels determined from seven individual firing tests are shown together with the calculated I_{SP} .

Thrust	Mass Flow	I_{SP}
mN	mg/s	s
42.6	61.6	70.4
42.3	61.6	69.9
42.6	61.6	70.4
42.3	61.6	69.9
42.5	61.6	70.3
43.1	61.6	71.2
42.8	61.6	70.7

$$\text{Average } I_{SP} = 70.4 \text{ s} \pm 0.5 \text{ s}$$

Table 1. Measured thrust and calculated specific impulse for seven individual cold gas thruster firings.

Based on these thrust measurements the average I_{SP} of the AST nitrogen cold gas thruster at a mass flow of 61.6 mg/s could be determined to $70.4 \text{ s} \pm 0.5 \text{ s}$.

VI. Outlook

While the AST thrust balance in its present state surpasses its design goals it has the potential for further improvements to achieve even better resolution and less noise.

From our point of view the mechanical construction does not seem to have reached its limitations yet. Currently, a new version of the thrust balance based on a very similar mechanical design is build by AST which will have improved electronic components. At the moment the voice coil actuator is capable of generating a force in the range from -1.8 N to 1.8 N with an intrinsic resolution of 16 bit which becomes slightly enhanced by an interpolation technique. The new version of the thrust balance will use components with higher resolution and therefore show improved performance within the whole measurement range up to 1 N .

Additionally, a new voice coil current source dedicated to thrust noise measurements will be developed. It covers only a small thrust range which results in significantly improved resolution and less noise for this specific application.

In its present state the thrust balance electronics consist of standard type parts only. The use of low noise parts at critical sections of a new and improved circuit design is also expected to lead to a significantly reduction of the overall noise floor.

As an additional feature the new thrust balance will be equipped with a second, independent device for in-situ calibration which is based on a physical principles other than a voice coil actuator. This new device in combination with the existing second voice coil actuator will therefore provide two independent methods for in-situ calibration and as a result high accuracy for absolute thrust measurement.

Acknowledgments

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References

¹Cara, D. D. et al., “Performance verification of the μ NRIT-2.5 thruster on the Nanobalance facility” , *IEPC International Electric Propulsion Conference*, IEPC, Wiesbaden, Germany, 2011