Micro-Thrust Balance Testing and Characterization

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Abstract: The paper describes the performance of a micro-thrust balance. The balance is based on the nulled-pendulum principle. It was developed by the National Physical Laboratory under an ESA funding. The test campaign was carried out in the ESA Propulsion Laboratory in ESTEC, The Netherlands. Different sources of noise were identified and their effects evaluated. Environmental vibrations were the most important source of noise. The results of the measurements which fully characterize the balance in terms of accuracy, resolution, and thrust range will be presented.

I. Introduction

Low-noise micro-thrusters are fundamental for future space missions like MICROSCOPE, LISA Pathfinder, LISA and Darwin. These missions require accurate spacecraft attitude and position control reachable through precise thrust modulation. Field Effect Electric Propulsion (FEEP) and colloid thrusters are particularly appropriate for these missions,[1, 2] but they still need an extensive experimental characterization. Therefore, the direct measurement of the thrust generated by these thrusters is a fundamental step for the validation of these technologies and for the successful realization of space missions. Appositely designed thrust stands are needed in order to directly measure the thrust in a range between 1 and 100 μN with a resolution of sub-μN.

To date, only few balances in the world have the capability to measure thrust at μN level. They have been recently developed at research centers like JPL,[3] NASA Goddard Space flight Center,[4] ONERA,[5] Alenia Spazio-Istituto Colonnetti,[6] and Busek.[7] They are either torsional balances or pendulum based balances.

In this paper we present the performance of a balance expressly designed for measuring the thrust generated by FEEP. The FEEP micro-thrust balance was designed and manufactured by the National Physical Laboratory under an ESA Propulsion Laboratory (ESTEC) commission.[8] It was not possible to test a real FEEP thruster because of its unavailability at the time of the test campaign. Nevertheless, any effort was made in order to perform the tests in conditions as close as possible to the real conditions required and generated by the presence of a FEEP thruster. In particular the balance was tested in vacuum, at a controlled temperature of 40 °C, a real (not working) FEEP thruster along with its cesium tank was completely integrated into the balance, and the high voltage power feeding cables required by the thruster were connected.

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II. Balance description

A. Principle of operation

The balance is based on a simple nulled-pendulum principle. The thruster is positioned in a box suspended by wires. The box is free to swing along the direction of thrust only (constrained pendulum). A capacitive displacement sensor detects the movement of the pendulum. A force feedback control system commanded by the displacement signal exerts the force necessary to counteract the thrust and thus to restore the initial position of equilibrium. The output of the balance corresponds to the force necessary to restore the nulled position.

A dummy pendulum, nominally identical to the first one, is added to the balance as the measurement is very sensitive to tilt and environmental vibrations. A mass equivalent to the one of the thruster is positioned on it. The dummy is subjected only to disturbances. Therefore, subtracting its signal from the thruster pendulum signal helps to eliminate most of the effect of undesired inputs. Nevertheless, any difference between the two channels and rotational vibrations (which act in an opposite way on the two pendulums) still contribute to generate noise in the measurement.

B. Physical description

Figure 1 shows the balance set-up. Each pendulum consists of a Macor box suspended by five silica fibers. They are connected in such a way that only the movement along the direction of thrust is allowed. The fibers are attached to a Zerodur plate. This material was chosen for its very low coefficient of thermal expansion. An aluminium structure supports the Zerodur framework.

One part of the displacement sensor is mounted on the ceramic box, while the other is attached to the Zerodur framework. The solenoid/magnet force actuator which realizes the force feedback is mounted in a similar way: the magnet on the box, and the solenoid on the Zerodur framework.

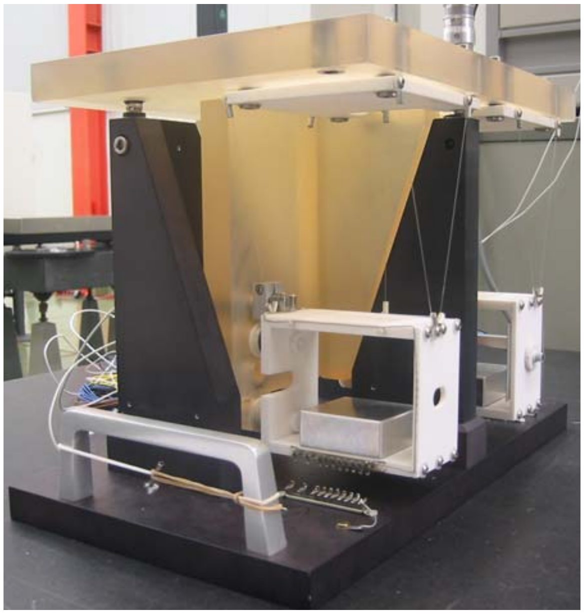

Figure 1. FEEP micro-thrust balance.

III. Experiment results

The balance was tested in atmosphere and in vacuum. A vacuum chamber was prepared for hosting the balance. The vacuum chamber was equipped with two pumps: a turbo-molecular pump for low-vacuum pumping, and an ion pump for high vacuum pumping down to 7 e-7 mbar. Only the ion pump was used during the tests as it does not have mechanical moving parts which could disturb the measurements. The balance was tested at different temperatures in order to characterize its sensitivity to temperature variations. The temperature in different locations of the balance was controlled by means of four halogen lamps and four temperature sensors (integrated circuits AD590).

The balance electronics provides outputs filtered at two frequencies: 1 and 10 Hz. In both cases an analog filter is used in order to avoid aliasing phenomena. Measurements were then digitally sampled at 50 Hz. This sampling frequency guarantees to reproduce the frequency content of the filtered signal.

A. Static calibration

The instrument was calibrated by exerting a known force history with steps ranging from 0 to 100 μN and recording the correspondent output. In this way, the relation between the input (force) and output (voltage) could be determined. The force was exerted by a solenoid/magnet force actuator, previously calibrated on a Mettler-Toledo AX504 precision balance.

Figure 2 shows the output versus the correspondent input. The circles represent the experimental data acquired, which correspond to the five force steps exerted. The line represents the linear interpolation of those data. The balance shows high linearity (standard uncertainty of 0.03 μN) and a static sensitivity of 0.123 V/μN (the theoretical static sensitivity was 0.1 V/μN).

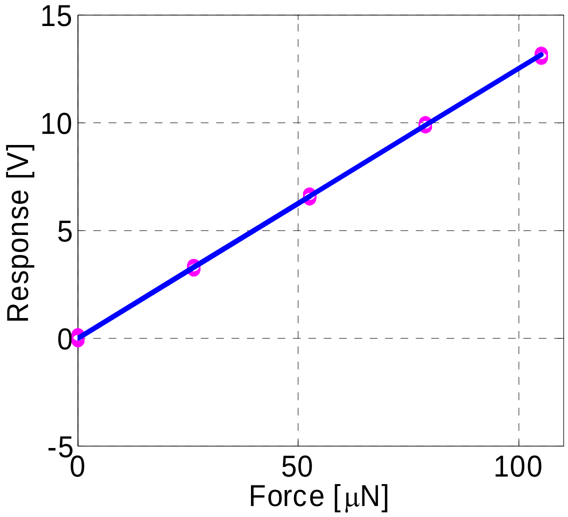

Figure 2. Calibration curve (line) and experimental data (circles). The input force is plotted versus the correspondent balance output.

B. Noise floor test

The noise figure expressed by the balance was evaluated by noise floor tests. This kind of test is carried out in order to verify whether the balance is suitable to test thrusters deemed to accurately control the spacecraft position. In fact, one of the strictest requirements on a thruster dedicated to precision missions is its noise figure. The intrinsic noise of the balance output sets a lower limit beyond which the thrust noise of the thruster cannot be measured.

During the noise floor tests, the output of the balance was recorded when no thrust force was exerted. The tests lasted up to 20.000 s with a sampling frequency of 50 Hz. Such a long time was required in order to detect the noise even at very low frequencies (10^{-4} Hz). In order to reduce the variance of the estimated periodogram, the noise spectral density was evaluated using the Welch's averaged modified periodogram method of spectral estimation.[9] The input signal was divided into eight sections of equal length, each with 50% overlap. Any remaining entries that could not be included in the eight segments of equal length were discarded. Each segment was windowed with a Hamming window. A Fast Fourier Transform was applied to the windowed data. The modified periodogram of each windowed segment was computed. The set of modified periodograms was averaged to form the spectrum estimate. The resulting spectrum estimate was scaled to compute the power spectral density.

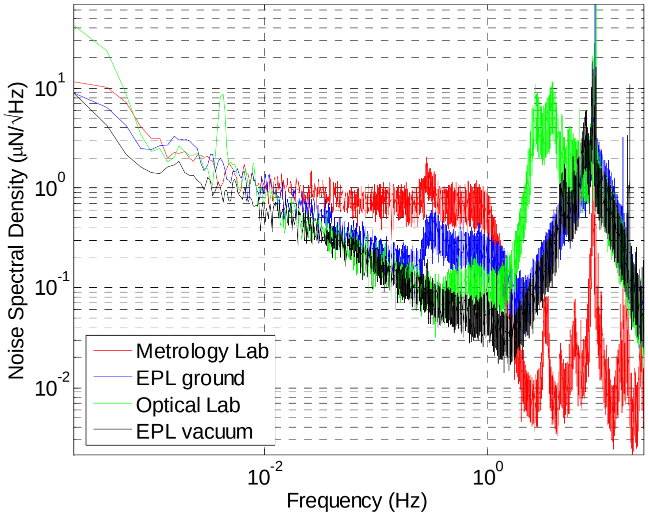

Figure 3. Noise spectral density obtained from noise floor tests in different environments.

Figure 3 shows the noise spectral density obtained in the different environments at ESTEC. In the Metrology Laboratory the balance was positioned on a granite block. The noise appears lower than in the others laboratories above 1 Hz because the signal filtered at 1 Hz was used in this plot. The signal filtered at 10 Hz was not available. In the Optical Laboratory the balance was positioned on a granite block suspended by a pneumatic damping system. In the ESA Propulsion Laboratory the balance was positioned on a small granite block and inside the vacuum chamber.

No clear explanation was found about the fact that the best low-noise performance was obtained when the balance was positioned inside the vacuum chamber.

C. Noise sensitivity to the mass of the thruster

The expected mass of the real thruster assembly is 400 g. The noise of the balance with different weights was measured to understand whether it is important to reduce the mass of the thruster in order to reduce the measurement noise. For this reason, two tests with different masses on both sides of the balance were compared.

Figure 4 shows the comparison between the noise spectral densities obtained with 400 g and 150 g. It is visible that the noise spectral density is up to 5 times lower above 0.1 Hz when a 150 g mass is used. This indicates that the mass of the thruster should be reduced as much as possible.

D. Noise sensitivity to unpaired loads

The level of noise cancellation realized by the dual system is directly dependent on the similarity of the two pendula. In order to verify this dependency, on one side of the balance was mounted a load 5% heavier than on the other side (420 g and 400 g respectively). The noise was then measured. Figure 5 shows how the noise of the measurement with unpaired masses is about 4 times higher in the frequency range between 0.2 and 2 Hz. This confirms that the mass of the dummy thruster should be carefully matched with the one of the real thruster. Any other source of asymmetry between the two channels should be eliminated or reduced.

E. Noise floor test with high voltage cables

FEEP thrusters require high voltage power feeding. For this reason two high voltage cables (Reynolds high voltage coaxial shielded cables AWG 26) connected the thruster on the pendulum to the fixed part of the balance. The same connection was made on the dummy side in order to recreate the same mechanical interference which the stiffness of the cables exerts on the pendulum (Figure 6).

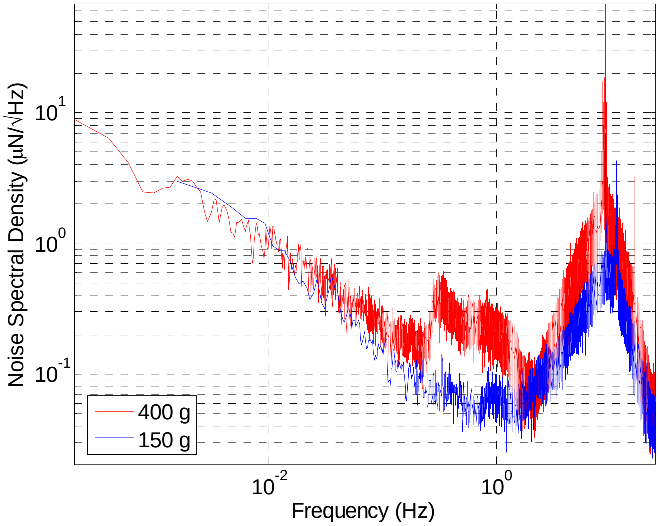

Figure 4. Noise spectral densities with different loads.

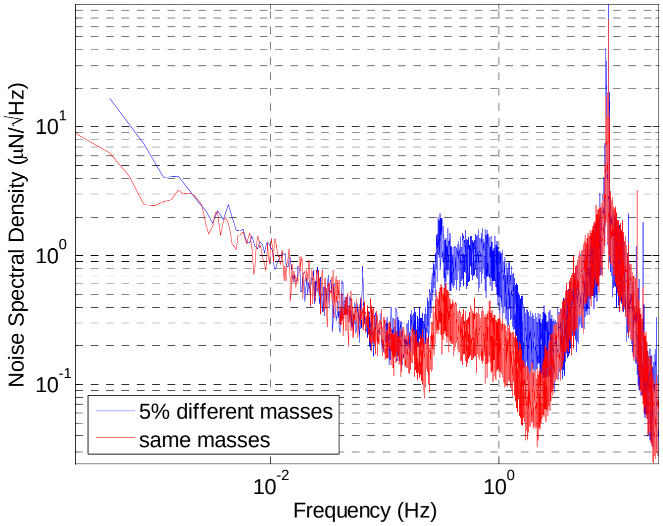

Figure 5. Noise spectral density with unpaired loads.

The presence of two high voltage cables connected to the thruster creates a mechanical interference on the pendulum and represents a source of asymmetry. Figure 7 shows the comparison of the noise spectral densities of the configurations with and without cables. The noise spectral density increases by a factor of 10 when the cables are present. This suggests that a study about both the best accommodation and best type of cables would give important improvements in the noise reduction.

F. Noise sensitivity to pumps vibrations

A test was carried out in order to verify the disturbance created by a running turbomolecular pump during a test phase. Figure 8 shows a comparison between the noise produced while using the turbomolecular pump and while using the ion pump. The situation with the turbomolecular pump running was expected to be noisier. The explanation of the similar response in the two situations is due to the fact that the vibrations induced by the turbomolecular pump have a high frequency content. In fact the pump spins at 1000 Hz. Those high frequencies are filtered both by the dynamic response of the balance and by the analog filter of the output of the balance.

This finding suggests that the balance could be tested even when the turbomolecular pump is working, with minor effect on the results. This is important because it takes more than 24 h before the ion pump can be activated and the turbomolecular pump turned off. Therefore even those 24 h can be used for testing.

IV. Conclusions

The test campaign permitted to fully characterize the balance from the metrological point of view. The balance showed a sensitivity of 0.123 V/µN, an uncertainty of nonlinearity of 0.03 µN (standard deviation), a measurement range 0-220 µN, a resolution of 0.3 µN without cables, and of 1.1 µN with high voltage cables. Considering the uncertainty introduced by the calibration setup (Mettler Toledo balance and solenoid/magnet force actuator), the total uncertainty of measurement is 2.5 µN (95% confidence) without high voltage cables and 3.3 µN with high voltage cables.

The tests showed the sensitivity of the balance to undesired inputs.

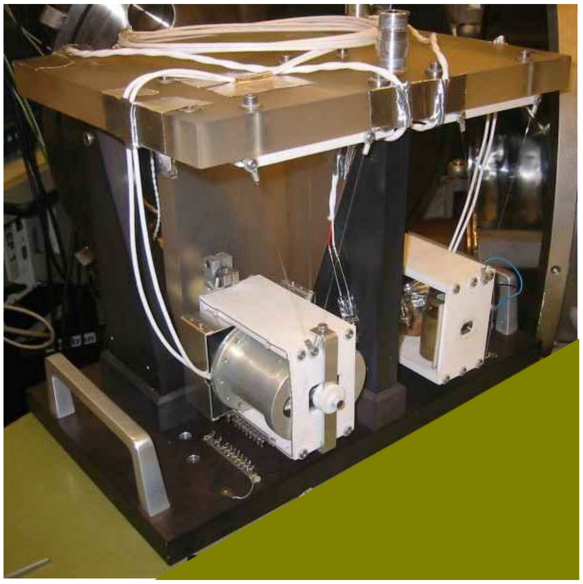

Figure 6. FEEP micro-thrust balance integrated with a FEEP thruster on the left side. The high voltage power feeding cables are visible (2 on each side).

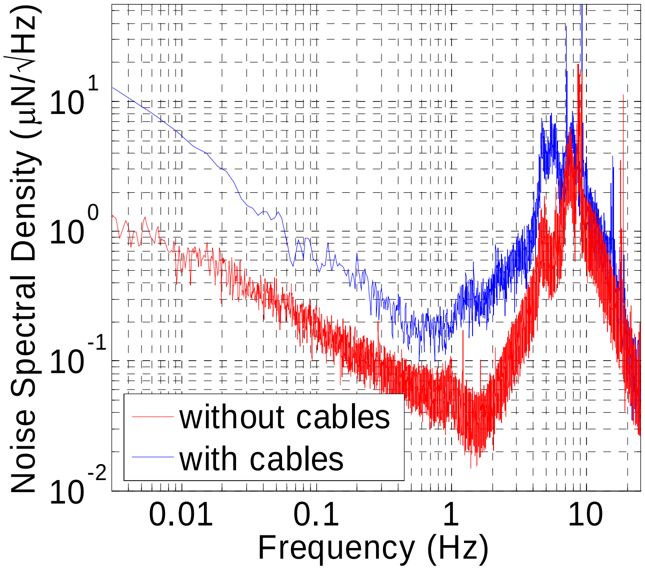

Figure 7. Comparison between the configurations with and without high voltage cables.

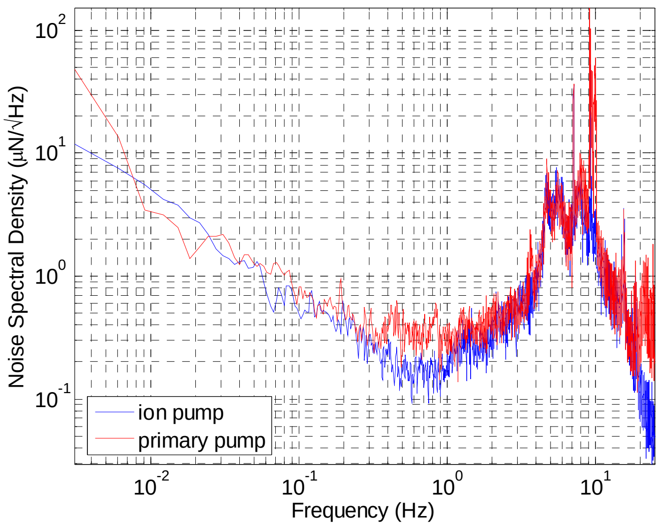

Figure 8. Comparison between the noise produced when turbomolecular and ion pump are working respectively.

Acknowledgements

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References

[1] Andrenucci, M., Marcuccio, S., and Genovese, A., "The use of FEEP systems for micronewton thrust level mission," *AIAA-93-2390*, 1993.

[2] Mueller, J., "Thruster options for microspacecraft: a review and evaluation of state-of-the-art and emerging technologies," *Progess in Astronautics and Aeronautics AIAA*, Vol. 187, 2000, pp. 45-137.

[3] Ziemer, J. K., "Performance measurements using a sub-micronewton resolution thrust stand," *Proceedings of the 27th International Electric Propulsion Conference*, Pasadena, CA, IEPC-01-238, 2001.

[4] Merkowitz, S., M., Maghami, P. G., Sharma, A., Willis, W. D., and Zakrzwski, C. M. "A µNewton thrust stand for LISA," *Classical and Quantum Gravity*, Vol. 19, 2002, pp. 1745-1750.

[5] Bonnet, J., Marque, J. P., and Ory, M., "Development of a thrust balance in the micronewton range," *Proceedings of the 3rd International Conference on Spacecraft Propulsion*, ESA SP-465, 2000.

[6] Canuto, E., and Rolino, A., "Nanobalance: An automated interferometric balance for micro-thrust measurement," *ISA Transactions*, Vol. 43, 2004, pp. 169-187.

[7] Gamero-Castaño, M., "A torsional balance for the characterization of microNewton thrusters," *Review of Scientific Instruments*, Vol. 74, 2003, pp. 4509-4515.

[8] Nicolini, D., Chesta, E., Gonzalez del Amo, J., Saccoccia, G., Hughes, E. B., and Oldfield, S., "FEEP-5 thrust validation in the 10-100 µN range with a simple nulled-pendulum thrust stand: integration procedures," *Proceedings of the 27th International Electric Propulsion Conference*, Pasadena, CA, IEPC-01-288, 2001.

[9] Welch, P., D., "The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms," *IEEE Transactions on Audio and Electroacoustics*, Vol. AU-15, 1967, pp. 70-73.