Thrust Measurements with the ONERA Micronewton Balance

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Abstract: The micronewton thrust balance developed at ONERA is presented, and is applied to thrust measurements with an Indium FEEP thrusters and a cold gas thruster. The principle of the balance and of the calibration are detailed, and the post-processing methods are illustrated. Currently the noise performance of the balance with a cold gas thruster is 1µN/√Hz in the frequency range [10^{-3} - 4 Hz] and 0.1µN/√Hz in the smaller frequency range [10^{-2} - 1 Hz].

I. Introduction

The positioning of satellites requires higher and higher precision as new space missions are developed. Precision is needed both in attitude control, for target pointing, and in position control, for absolute positioning in drag-free experiments, or relative positioning in formation flying. Because of the higher accuracy and resolution needed, and the lower mass of some scientific satellites, thrusters with performances on the order of 1 µN are currently needed. New scientific missions in Europe with a need for micronewton thrusters include Microscope, Aspics, Max, Pegase and SIMBOL'X from CNES, and Gaia, LISA Pathfinder and LISA from ESA.
Micronewton thrusters are being developed and qualified to address the requirements of these new space missions, but one of the challenges of the ground characterization of these thrusters is the actual measurement of their thrust. Different balances exist for micronewton thruster characterization: at Alenia (Italy)[1], at Buseck (USA)[2,3], at NASA Godard (USA)[4], at Marotta (UK)[5], at ARCS (Austria)[6,7], and at ESTEC (Netherlands)[8,9]. But few thrust balances, if any, are currently able to measure the most stringent space mission requirements in both resolution and bandwidth. Currently, the typical required values for the noise and bandwidth are on the order of 1 µN/√Hz and [10^{-2} Hz – 10 Hz], respectively. Not only does the balance need to have an intrinsic noise level within these values, but it also needs to maintain this performance when fitted with a flight model thruster. This is a challenging aspect of micronewton thrust measurements, because of the different constraints imposed by the operation of the thrusters. For example, a FEEP thruster has high voltage cables which may create electromagnetic forces disturbing the measurements, and a cold gas thruster has an inlet tubing which may greatly increase the stiffness of the balance.
ONERA has been developing a micronewton balance since 1999 in order to fill the need for a thrust stand for missions such as Microscope. The balance has been successfully tested in the range [1 µN - 20 µN] with an Indium FEEP thruster from Austrian Research Center at Seiberdorff (ARCs) in 2001. In the past two years, the performances have been significantly improved in the framework of a contract with CNES, and the balance has been applied to cold gas thruster measurement in collaboration with Bradford Engineering.
Although the balance facility is in constant evolution and still improving (other major improvements are planned in the coming year, especially regarding the bandwidth), the performance is now compatible with several space missions and flight model thrust measurements are planned.

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This paper presents the current balance general design and performance, and thrust measurements already made with FEEP thrusters and cold gas thrusters.

II. Principle of the balance:

The ONERA micronewton balance is a vertical pendulum (Figure 1). In the basic configuration, the thruster applies a horizontal force on the pendulum, which then moves from its initial vertical position to a new, tilted equilibrium position. In this tilted position the torques of the thrust and of the weight of the pendulum cancel each other. The angle of the pendulum is then a linear measure of the thrust.
A vertical pendulum has two advantages compared to other balance types (torsion and wight balance):
- the frictionless pivot and equilibration is simple
- the thrust calibration can be done in an absolute manner with calibrated weights; this will be described in a later section

Displacement sensors are placed on the pendulum to measure the angle and two different types of sensors are used. One is an accelerometer (Honeywell QA 2000) whose axis measures the projection $\gamma_{//}$ of gravity when the pendulum tilts. It is also used as a verticality reference. The other sensor is a capacitive sensor (Fogale, MC900) which measures the linear movement of the bottom of the pendulum.

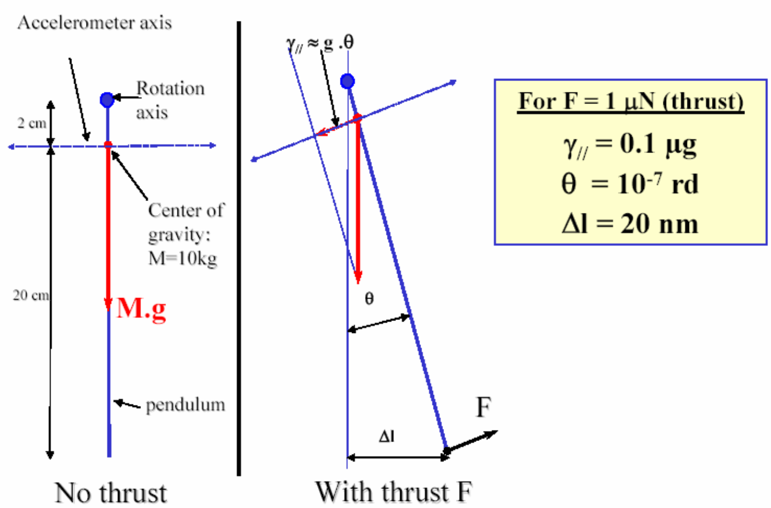


Figure 1. Principle of the ONERA micronewton balance.

A more detailed schematic of the balance is shown in Figure 2. All the displacement sensors are shown:
- two accelerometers: one on the pendulum for tilt measurement, one on the balance support to measure the tilt of the vacuum tank due to ground and structure vibration.
- two capacitive sensors on the pendulum arm (only one is represented).

The basic difference between the two types of sensor is the reference used for measurements: for the accelerometers it is the gravity, for the capacitive sensors it is the counter electrode attached to the structure of the vacuum tank.
Out of the four sensors, only one is theoretically needed to measure the tilt of the balance. But the use of different sensors, at varying places with different physical principles and reference proved very useful for the tune up of the balance and the observation of the vibrational modes of the pendulum and support structure.
The pendulum is of the compound type, where a moving counterweight is used to change the position of the centre of gravity of the system, thus changing the sensitivity and natural frequency of the balance. Typically the natural frequency used in experiments is 0.3 Hz.
At the bottom of the pendulum two actuators are placed. The first one is a copper plate moving close to a permanent magnet: this is the frictionless, Foucault current damping system, which allows the pendulum to be near optimum

damping. The second one is a coil moving also near a permanent magnet on the vacuum tank. By making a current flow through the coil, a force is applied on the balance: this is the actuator. One of the characteristics is its linearity: because the movement of the coil is frictionless and is very small (<1 µm) compared to the gradient of magnetic field of the magnet, the force is very much proportional to the current.
The axis of rotation is a frictionless pivot: the pendulum is suspended with two blades.

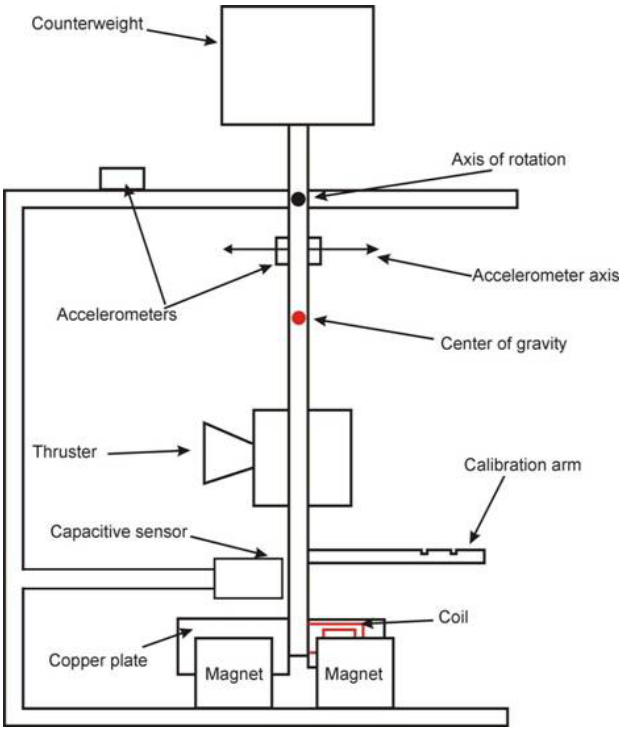


Figure 2. Configuration of the balance.

Two measurement modes can be used:
- open loop : as described above, the pendulum is free to move
- closed loop: a feedback loop uses the coil actuator to maintain the pendulum vertical as the thrust is applied; the current through the actuator is then a measure of the thrust. This mode has one clear advantage: the movement of the pendulum becomes second order. This can be important if the movement of the pendulum is perturbed by nonlinear flexure phenomena (plastic deformation of cables, hysteresis, etc…), because these are dramatically reduced. In our case the perturbations create less than 5% error in open loop, thus closed loop operation does not seem mandatory.

Finally, two balance configurations can be used.
- the horizontal configuration: it is the one described so far, where the thrust vector is horizontal (Figure 3, left); this configuration is best for FEEP thrusters
- the vertical configuration: the thruster is mounted on an horizontal arm, and the thrust vector is vertical (Figure 3, right); this configuration is best for cold gas thrusters

The reason for the use of the vertical configuration lies in the internal, longitudinal valve movement of cold gas thrusters. In the horizontal configuration, the valve shift (when it is opened or closed) changes the mass distribution of the pendulum, and thus creates a tilt of the pendulum. This tilt can be confused with the action of a thrust. This problem is compounded by the fact that the movement of the valve is not easily predictable (hysteresis in piezo-actuated thrusters, heating in coil-actuated thrusters). In contrast, in the vertical configuration the longitudinal

position of the valve is not important for the equilibrium of the pendulum, and thus only a thrust can affect the pendulum.
If the length of the horizontal arm is the same as the length of the vertical arm (170 mm in our case), and if we ignore the added mass of the arm, the thrust sensitivity will be the same in both configurations because the torque created by the thrust is the same in both cases (T.L in Figure 3 ; T=thrust, L=arm length).

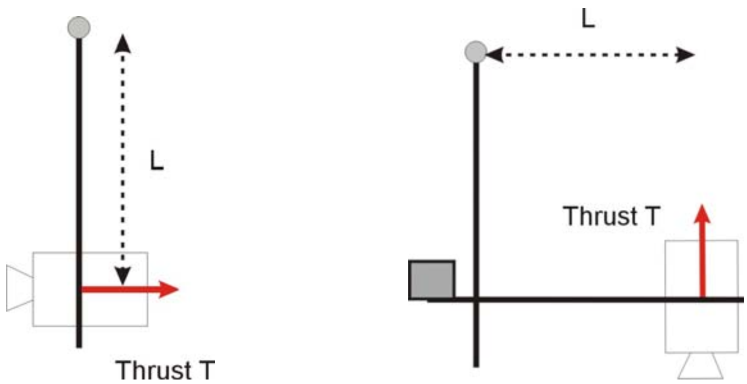
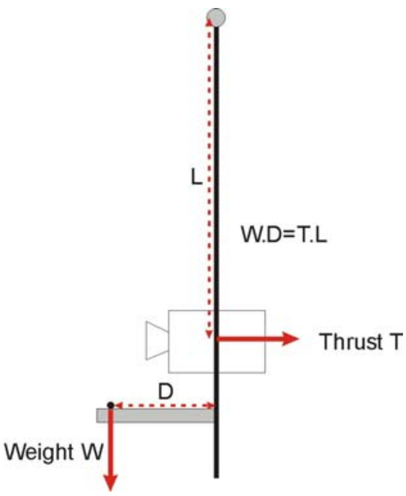


Figure 3. The two balance configurations: horizontal configuration (left) and vertical configuration (right).

III. Calibration principle

One of the advantages of a pendulum balance is that it allows for an absolute and precise thrust calibration. The principle is to deposit masses on a small horizontal arm attached to the pendulum. The calibration arm schematic is visible in Figure 2 and is shown in more detail in Figure 4. Weights of small masses can be calibrated very precisely with a weight balance: 1% accuracy for a 10 mg mass, typical of the masses used, is easily achievable. These masses are placed on a vertical, vacuum-rated translation stage. The calibration can thus be operated in vacuum, in the same exact conditions as the thrust measurements. For calibration different masses can be sequentially deposited on the calibration arm, thus imposing calibrated torques on the balance. This is shown in Figure 4.



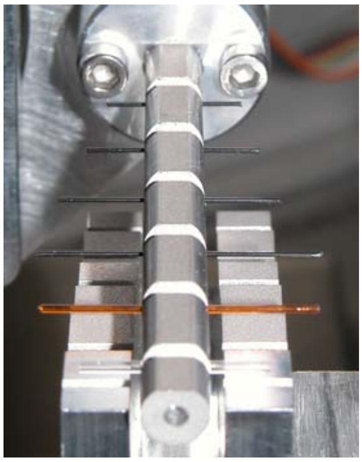


Figure 4. Principle of thrust calibration (left) and image of six masses deposited on the calibration arm (right).

In fact what is calibrated is the torque. If the measured signal is S for a weight W, we obtain a calibration factor α=S/(W.D) en Volt/(N.m). Then, during the measurement of a thrust T with signal St, we deduce the torque of the thrust St/α and since it is equal to T.L, we deduce T. In order to check for linearity over the whole range of the balance, we can use several calibrated masses that are deposited sequentially at different positions on the calibration arm (Figure 4, right). For the lower thrust range (< 10 μN), it is not practical to use masses for calibration. We then use the actuator coil, which has a linear behaviour. The calibration from the coil is matched to the absolute masses calibration on the higher thrust range, and it allows us to calibrate and check linearity down to 0.1 μN.

IV. Design of the facility

The vacuum tank used for the measurements is 50 cm in diameter and 70 cm long. A turbomolecular pump with pumping speed 1000 l/s for N_2 yields a limit vacuum < 10^{-6} mbar. Typically, with a cold gas thruster of Isp 50 and a thrust of 500 μN, the vacuum is about 10^{-3} mbar. The balance has been conceived with the Software Solidworks, and CAD drawings are shown in Figure 5. The arm of the pendulum is a made of aluminum. The balance assembly is then installed in the vacuum tank (Figure 5).

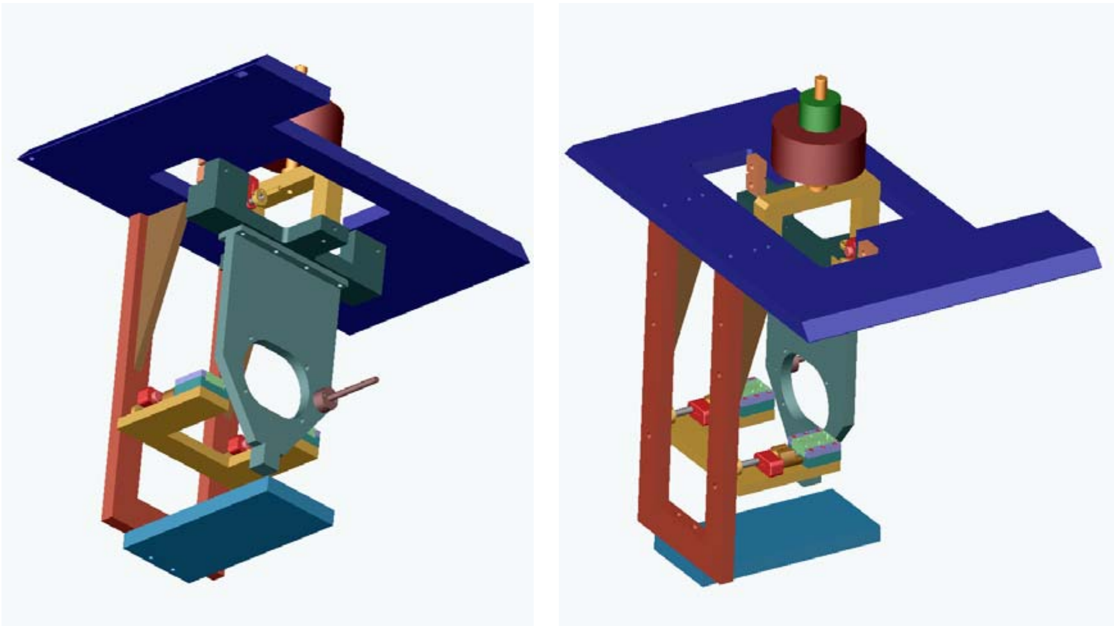


Figure 5. CAD views of the micronewton balance assembly.

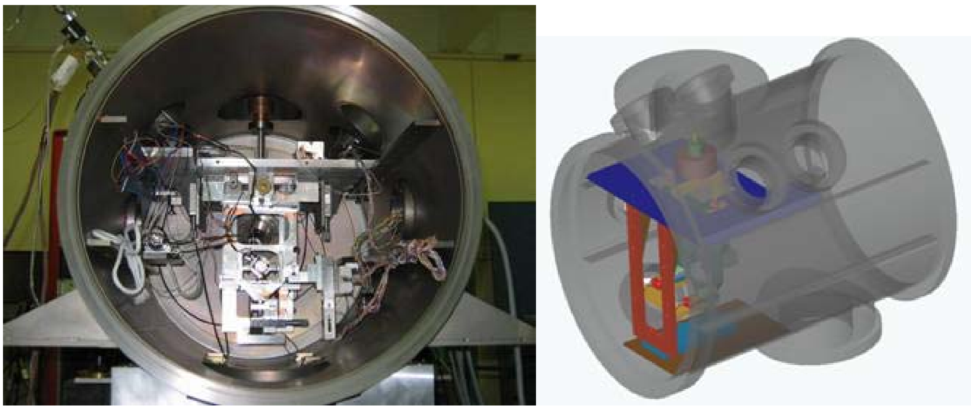


Figure 6. Views of the balance installed in the vacuum tank.

The four sensors (capacitive and accelerometric) are linked to vacuum-rated actuators allowing to zero the readings while the thrusters and balance are in vacuum. The noise of the sensors, electronic and acquisition chain is negligible in all measurements (< 0.01 µN/√Hz).

Six temperature sensors are placed in different parts of the tank and balance assembly. They have a resolution of 0.01 °C and an accuracy of 0.05 °C. They allow checking the thermal stability of the balance, which is important to avoid a drift in the thrust signal.
The balance is mounted on a support structure that has been recently stiffened in order to increase its resonant frequency from 10 Hz to 25 Hz.

V. Performance of the balance

A. Measured noise
All the performances have been measured with an MTA thruster from Bradford Engineering mounted on the pendulum, connected to the pressurized gas inlet and in vacuum, i.e. in actual thrust measurement conditions and ready to go. As mentioned before, we believe the performances must be assessed in such a way in order to be representative of thrust measurements. Thus no performance data will be presented of the balance by itself, with no thrusters mounted (although the data would obviously be better). The capacitive sensor was used for tilt measurement.

In order to put the measured noise in perspective, a model of the pendulum must be used. It is described as a second order system whose input is the thrust and whose output is the response of the capacitive sensor. This system is represented by the transfer function:

$$\frac{G_{cap}}{G_T}(i\omega) = \frac{S_{cap}}{\left(\frac{i\omega}{\omega_0}\right)^2 + 2\zeta\frac{i\omega}{\omega_0} + 1}$$

where the parameters: S_{cap}, ω_0, ζ represent respectively the sensitivity, the natural frequency and the damping coefficient of the balance. The experimental determination of the values of these parameters makes it possible to draw the Bode plot (amplitude) of the transfer function of the balance (Figure 7).

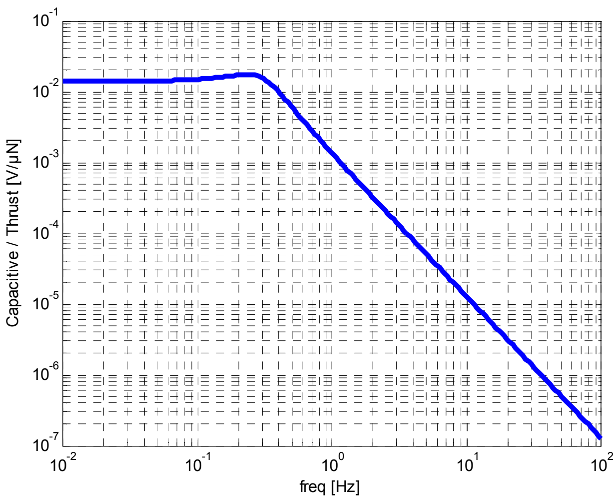


Figure 7. Bode plot of the capacitive sensor response to thrust

This will help interpret the balance noise. The noise of the signal was measured with no thrust applied, and the PSD is shown in Figure 8. Also shown is the PSD of the response of the balance when it is excited by a thrust signal with a constant frequency content of 1 μN/Hz$^{0.5}$. The two lines cross at about 4 Hz. This gives an indication of the frequency band that it is possible to use in order to make measurements at μN level.

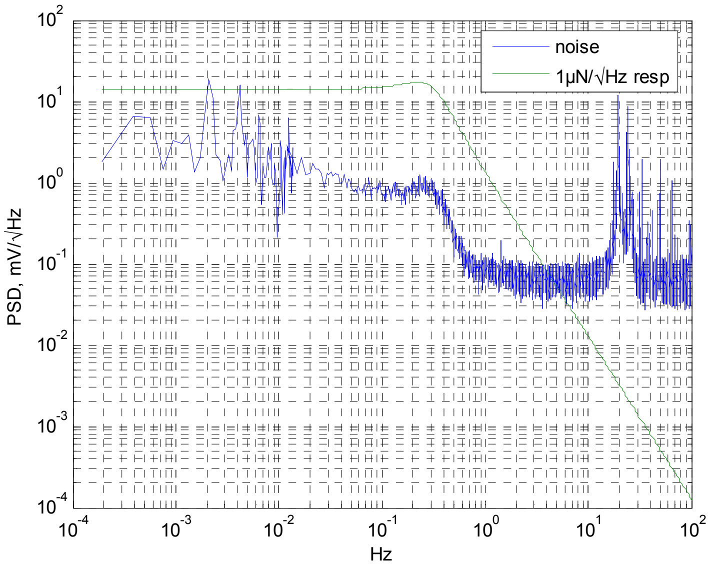


Figure 8. Comparison of the PSD of the response of the balance when it is excited by a thrust signal with a frequency content of 1 μN/Hz$^{0.5}$ with the PSD of the noise floor measured with the capacitive sensor.

When we divide the PSD of the noise by the transfer function of the balance of Figure 7, we obtain the equivalent thrust noise in μN/Hz$^{0.5}$. This is shown in Figure 9.

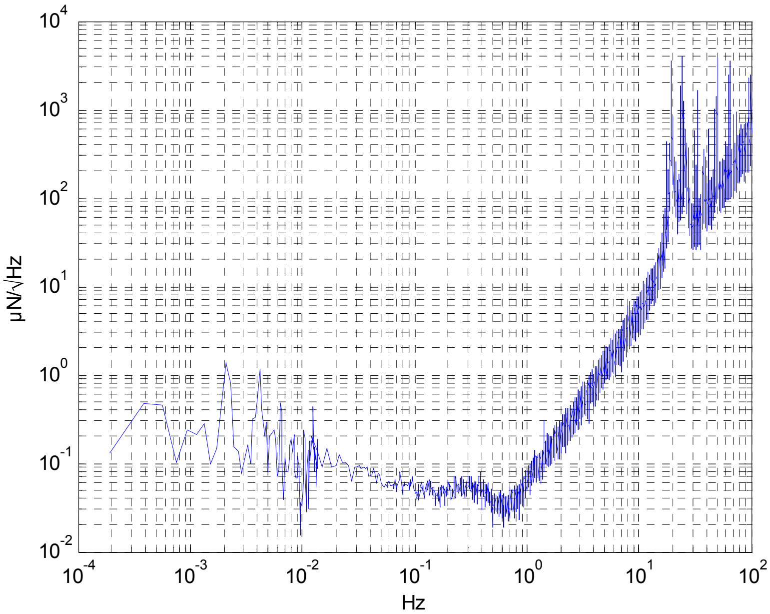


Figure 9. Equivalent thrust noise due to the balance floor noise.

From Figure 9 it is possible, by integration, to obtain the noise RMS as a function of the cut-off frequency of the low-pass filter which is applied to the signal. It is shown in Figure 10. As can be seen a noise RMS of 0.1 μN is obtained with a bandwidth of 1 Hz (about 1 s response time) and a noise RMS of 1 µN is obtained with a bandwidth of about 4 Hz (0.25 s response time).

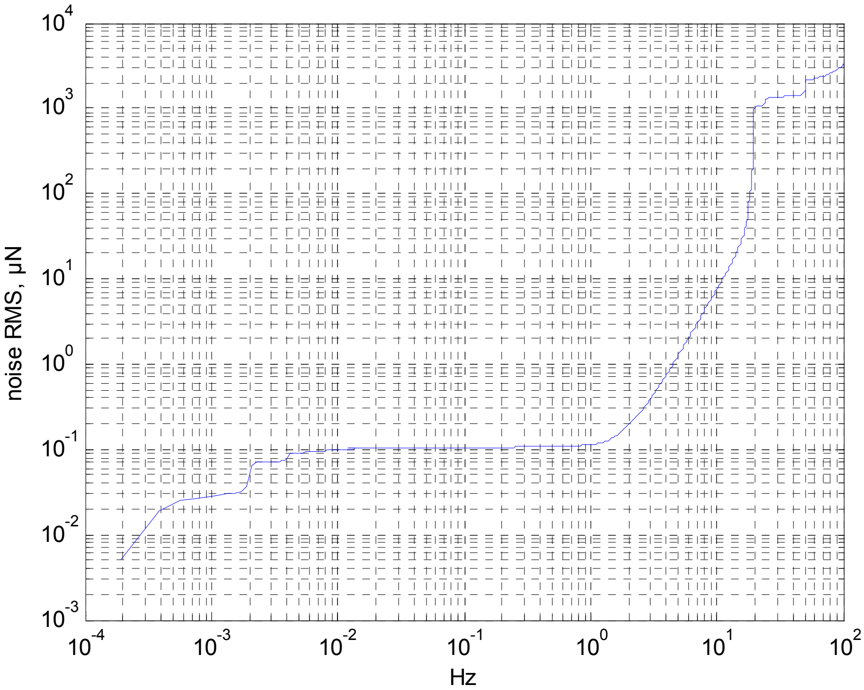


Figure 10. Noise RMS as a function of the cut-off frequency of the low-pass filter which is applied to the signal.

B. Post-processing: reconstruction of the input thrust signal from the output signal

The raw data from the balance shows damped oscillations when responding to a thrust step (Figure 11), with a period of about 0.3 Hz (the period of the balance), thus it would seem that the time response is no better than 3 to 10 s. In fact this is not the case, because the signal can be improved with the knowledge of the balance response: **the original signal can be reconstructed** with a bandwidth that can be chosen by filtering the data, but with a noise that is given by Figure 10.

The key element is that the balance behaves nearly as a perfect under-damped 2^{nd} order low-pass filter (this was checked experimentally). In order to recover the higher frequencies it is then possible to divide the output by the transfer function (Figure 7) in the frequency domain. This permits to recover the high frequency content of the signal. This procedure would give a perfect reconstruction of the input if the output were not affected by noise. When noise is present the reconstruction may be very noisy because the high frequency noise may be magnified by several orders of magnitudes (this is the large increase in Figure 10). For this reason the output signal has been low-pass filtered at 1 Hz in the following figures before dividing it by the transfer function.

Figure 12 shows the response of the balance and the input reconstruction of a step input of 21 µN (left) and 1 µN (right). In both cases the time response is less than 1 s with the input reconstruction.

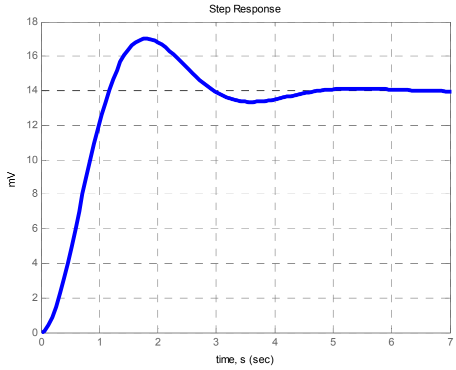


Figure 11. Theoretical response of an under-damped 2nd order low-pass filter to a step input

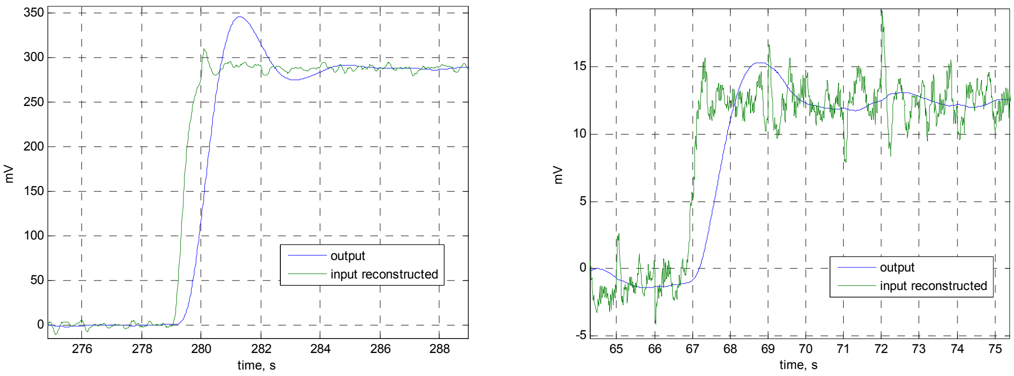


Figure 12. Input reconstruction of a 21 µN step input (left) and of a 1 µN step input (right) with a 1 Hz, second-order filter.

In fact it can be shown that this procedure produces a result equivalent, in terms of time response and signal-to-noise ratio, as the use of a feedback loop maintaining the pendulum vertical (closed-loop mode).

C. Step response, linearity, repeatability and drift

Figure 13 shows the calibration signal with two masses deposited successively, corresponding to thrusts of 36 µN and 143 µN, respectively. The thrust sensitivity is measured to be within 3% for both cases, at about 14.6 mV/µN, thus showing the linearity of the balance.

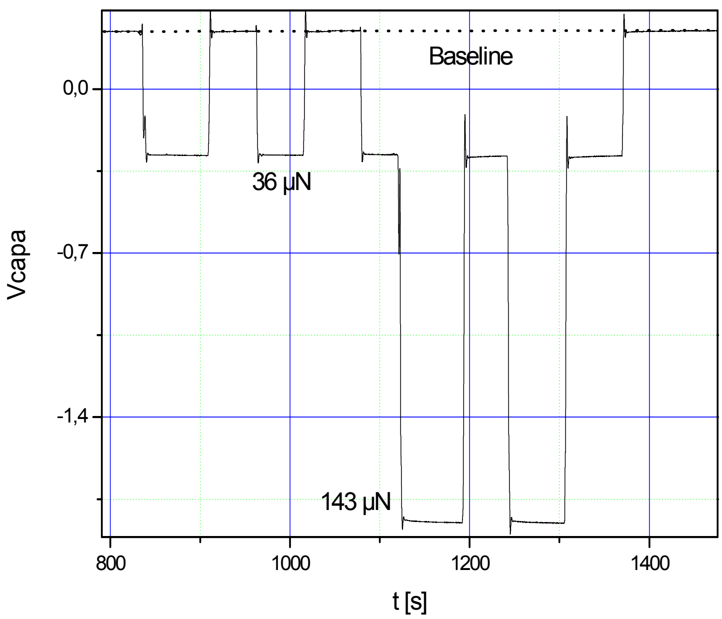


Figure 13. Absolute calibration with two masses deposited successively (raw data).

The calibration of the coil actuator gives 35 µA/µN, and this actuator allows checking linearity and performance at lower thrusts.
Example of two reconstructed square steps with the coil actuator (20 µN and 1µN) and a bandwidth of 1Hz are presented in Figure 14.

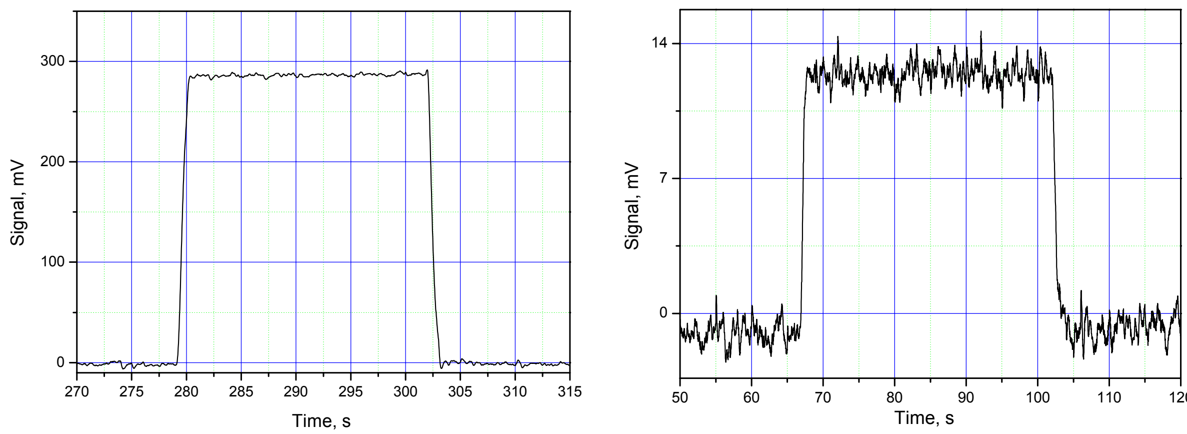


Figure 14. 20 µN step (left) and 1 µN step (right) applied with the coil actuator and a bandwidth of 1 Hz (4th order filter). The rise time is about 1 s.

The repeatability and drift are illustrated in Figure 15. The drift is less than 0.5 µN in 10 mn.

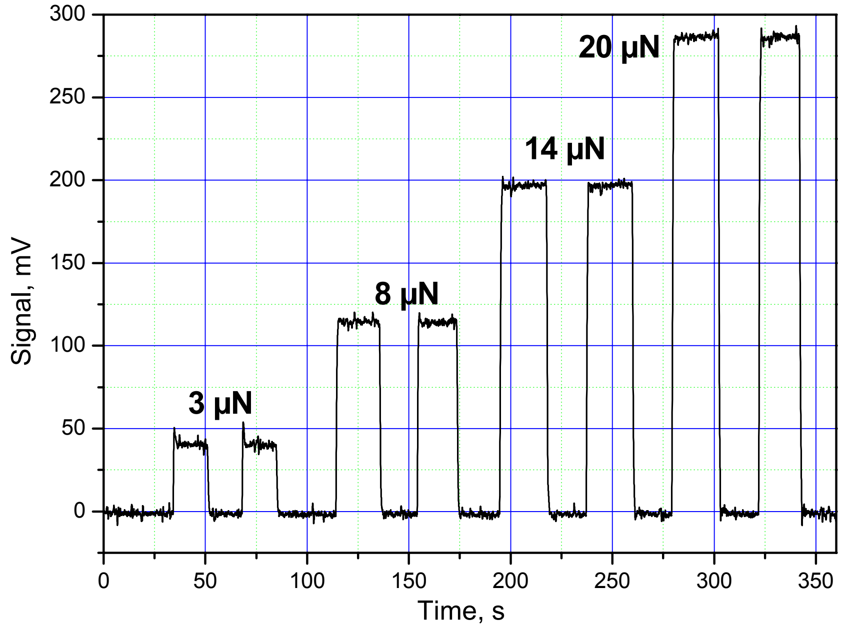


Figure 15. Thrust steps with the coil actuator (1 Hz bandwidth with a 4th order filter).

D. Thrust range

The single shot dynamic range of the balance is currently [0.1 µN, 3mN] for a 1Hz bandwidth, which represents an amplitude of $3x10^4$. This is illustrated in Figure 16.

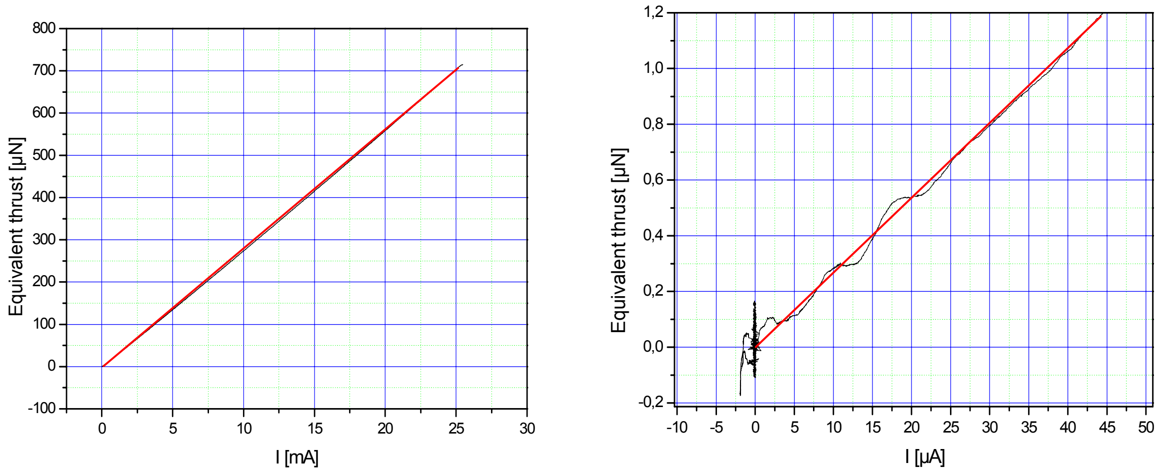


Figure 16. Thrust measurements with the actuator coil showing part of the thrust range of the balance: up to 700 µN (left) and down to 0.1 µN (right). The data is in black, and the red line is a linear fit. The bandwidth is 1 Hz, and no reconstruction post-processing has been applied (hence the small oscillations).

VI. Thrust measurements

Thrust measurements on a preliminary version of the balance are presented for a FEEP thruster and a cold gas thruster. The Indium FEEP thruster is from ARCS (Austrian Research Center Seibersdorff), and has a maximum thrust of 20 µN for a measured current of 200 µA. These early measurements (made in 2001) as a function of the FEEP thruster current are shown in Figure 17.

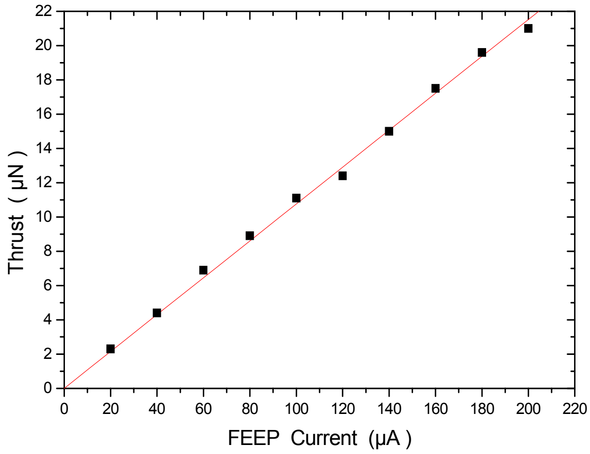


Figure 17. Thrust measurement on an Indium FEEP by ARCS (Austrian Research Center Seibersdoff) with the ONERA micronewton balance.

A thrust measurement made more recently (2006) with a cold gas thruster (MTA) by Bradford Engineering[10,11] as a function of the nitrogen flowrate is presented in Figure 18.

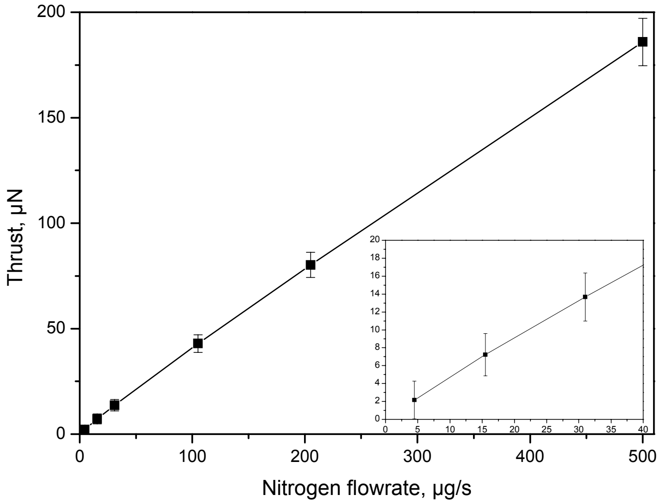


Figure 18. Thrust measurement on a Bradford Engineering cold gas thruster (MTA).

The error bars correspond to uncertainties due to the piezo-activated valve movement inside the thruster. When the valve moves, the hysteresis of the piezoelectric material prevents us to know its exact state, thus it is difficult to subtract accurately its contribution from the measured thrust at low thrust levels (typically the contribution of the valve movement can be larger than 10 µN). However all the measurements were made in the horizontal configuration (Figure 3). The vertical configuration of the balance is more interesting for cold gas thrusters because it is insensitive to longitudinal mass movements. This configuration is currently being investigated, and the latest results obtained show that, for the same thrust sensitivity, the vertical configuration is at least 15 times less sensitive to the valve movement than the horizontal configuration. Given the latest experiments, it seems possible to decrease the sensitivity to zero altogether, and this is being currently tested. That would allow a complete study of cold gas thrusters (thrust, Isp, etc....) at thrust levels smaller than 10µN.

VII. Conclusion

The micronewton balance facility at ONERA has been successfully improved in the past two years, in terms of balance design, material, sensors, actuators, support structure, data acquisition and data processing. The resulting performance where measured with an operational cold gas thruster mounted: 1µN/√Hz in the frequency range [10^{-3} - 4 Hz] and 0.1µN/√Hz in the smaller frequency range [10^{-2} - 1 Hz].

In the next two months, the horizontal configuration will be tested with two cold gas thruster technologies from Bradford engineering (MTA and PMT), and a closed loop system will be tested in order maintain the arm vertical. In the near future, improvements to the design of the support structure will be tested in order to remove the 25 Hz resonance peak and allow and increase of the bandwidth of the balance up to 10 Hz, from 4 Hz currently.

Other measurement modes will be tested, such as measuring the actual mass displacement inside a thruster (which could be an issue for satellites), and measuring the side thrust for an assessment of the angular stability. The nitrogen plume of the cold gas thruster will also be investigated by optical mean for high-bandwidth density and velocity measurements (investigation ongoing). Finally the applicability of the balance for pulsed thrusters such as PPT will be assessed, with possible tests in 2008. The goal is to complete a test facility for the characterization and qualification of flight model micronewton thrusters.

Acknowledgments

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