

Direct Thrust Measurement of a Vacuum Arc Thruster

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Abstract: This paper presents the experimental characterization of a vacuum arc thruster on a thrust balance. A prototype of the Plasma Jet Pack (PJP) thruster, with an energy of 2.04 J/pulse, has been installed on ONERA micronewton thrust balance. Measurements of the thrust have been performed at different pulse repetition frequencies. The mean thrust value is between 57 μN (at 2 Hz) and 288 μN (at 10 Hz). The impulse bit has been measured on 120 single discharges. The mean Ibit is 29.2 $\mu\text{N.s}$, in line with the value inferred from mean thrust measurements.

Nomenclature

c	=	damping coefficient of the balance
C_m	=	calibration coefficient of the balance for steady thrust
C_{coil}	=	actuation coefficient of the coil
C_{pulse}	=	calibration coefficient of the balance for pulsed thrust
D	=	position of the calibration masses on the horizontal arm (mass leverage)
f_{VAT}	=	repetition frequency of the discharges in the VAT thruster
G	=	balance sensitivity
I_{bit}	=	impulse bit
k	=	stiffness of the blades
L	=	distance between the axis of rotation and the thruster on the pendulum
M	=	mass of the pendulum arm
r_G	=	distance between the axis of rotation and the center of mass of the pendulum
V_{cap}	=	balance signal (capacitive sensor)
T_m	=	mean thrust
T_{eq}	=	equivalent thrust produced by the deposition of the masses or the coil actuator
V_{coil}	=	voltage applied to the coil
V_{OI}	=	amplitude of the first oscillation of balance signal after a thrust impulse
W	=	weight of the calibration masses
w_p	=	width of the square pulse of voltage applied to the coil
α	=	calibration factor of the coil
ε	=	damping ratio
θ	=	angle of deflection of the pendulum
ω_0	=	natural frequency of the pendulum

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I. Introduction

THE development of small and nano-satellites for scientific missions and communications has opened a new market for lightweight, low thrust (micronewton and millinewton range) electric propulsion systems. Among the emerging technologies, the vacuum arc thruster (VAT) is a promising technology for micro-propulsion because of its capability to produce high velocity ions with a pulsed arc discharge, without the need of an additional electric or magnetic field.

One of the challenges of the ground characterization of VAT thrusters is the actual measurement of their thrust, which is a fundamental step in the validation of their performances. The thrust consists of short pulses, with a duration of a few tens of microseconds, which is much smaller than the typical time response of a thrust balance.

This paper presents direct thrust measurements of the Plasma Jet Pack (PJP) thruster on ONERA micronewton balance. PJP is a 30 W vacuum arc thruster developed by COMAT [1]. Two types of measurements have been performed in this work:

- mean thrust (in μN), which is obtained when the thruster is operated at a given pulse repetition frequency in steady-state mode ;
- impulse bit (or Ibit, in $\mu\text{N.s}$), which is measured on separate arc discharges.

The Section II describes PJP thruster, along with the thrust balance and the calibration procedures. The impulse response function of the balance is detailed in Section III. Finally, the results of the thruster characterization are presented in Section IV for several operating conditions.

II. Apparatus and methods

A. Vacuum arc thruster

The principle of the vacuum arc thruster consists in eroding solid metal propellant thanks to electrical discharge in vacuum. After the ignition, an electric breakdown takes place between cathode and anode electrodes. An arc forms with a high current (10 -100 A) and low arc voltages. During the arc phase, the cathode is ablated, and metallic vapors are heated and ionized. Plasma is accelerated by electromagnetic forces and ejected from the thruster.

COMAT is currently developing the 30W Plasma Jet Pack thruster. Recent measurements with a triple Langmuir probe have shown that the ion velocity is around 60 km/s for a discharge energy of 1J [1].

For the prototype under test, the energy stored in the capacitors is about 2.04 J, and the thruster can be operated at a frequency up to 10 Hz. The thruster is powered by an external DC power supply with a voltage of 14 V.

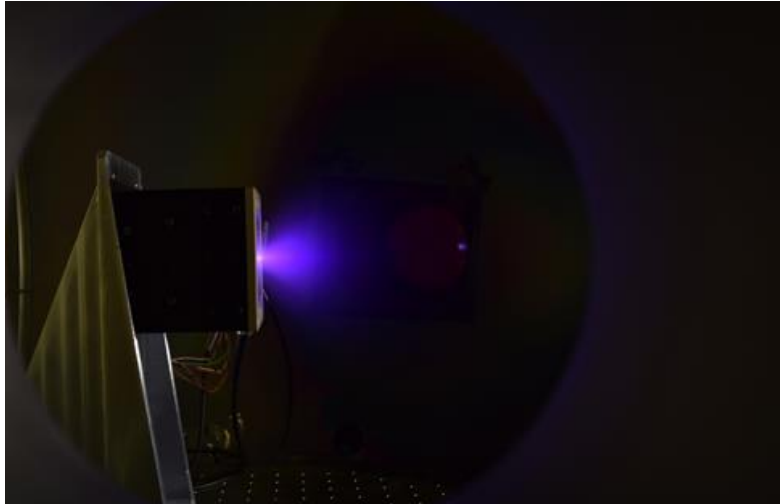


Figure 1. View of Plasma Jet Pack thruster.

B. ONERA micronewton thrust balance

ONERA has been developing a micronewton balance since 1999. ONERA micronewton thrust balance, whose thrust measurement range is 0.1-1000 μN , has been selected for thrust characterization of microthrusters for scientific missions such as GAIA, Euclid, LISA-Pathfinder and Microscope [2][3]. The balance is a vertical pendulum (see

Figure 2). The thruster is mounted at the end of the pendulum arm on which it applies a horizontal force. In the free pendulum mode, when the thruster is operated in steady-state mode (with a constant thrust), the arm then moves

from its initial position to a new, tilted, equilibrium position, where the torque exerted by the thrust and the torque exerted by the weight of the pendulum arm cancel each other. The angle of the pendulum is then a linear measure of the thrust, given that the angle is usually very small ($\ll 1$ degree).

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) for which the axis measures the projection of gravity when the pendulum tilts. It is also used as a vertical reference. The other sensor is a capacitive sensor (Fogale MC900), which measures the linear displacement of the bottom of the pendulum. The capacitive sensor is the one used for actual thrust measurement because of its higher signal-to-noise ratio, whereas the accelerometer is used as a vertical reference.

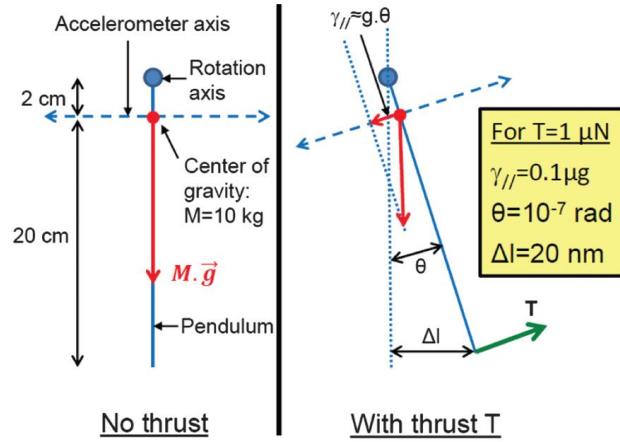


Figure 2. Principle of the ONERA micronewton balance, and order of magnitudes of characteristic displacements.

A more detailed schematic of the balance is shown in

Figure 3 with all displacement sensors: one accelerometer on the pendulum for tilt measurement, one accelerometer on the balance support to measure the tilt of vacuum tank due to ground vibrations, and the capacitive sensor on the pendulum arm. The pendulum is of compound type, with a moving counterweight that is used to change the position of the center of gravity of the system with respect to the axis of rotation, thus changing the sensitivity and the natural frequency of the pendulum. The axis of rotation is a frictionless pivot: the pendulum arm is suspended with four copper blades.

At the bottom of the pendulum, a copper plate (fixed on the arm) moves near a permanent magnet (placed on the vacuum chamber). This is the frictionless Foucault current damping system, which allows the pendulum to be near optimum damping. Next to the damping system, a coil actuator can be found. It consists of a planar coil (fixed on the arm) near a permanent magnet. By making a current flow through the coil, a force is applied on the balance. One of the characteristics is its linearity: because the movement of the coil is frictionless and is very small (less than $1 \mu\text{m}$) compared to the gradient of magnetic field of the permanent magnet, the force is very much proportional to the current through the coil, i.e. to the voltage applied to the coil.

Using a feedback loop with a PID controller, the thrust balance can be used in “null mode”, where the force applied by the actuator maintains the arm at its initial vertical position. In this study, the balance is used in the “free pendulum” mode. The coil actuator is used for the calibration of pulsed thrust described hereinafter.

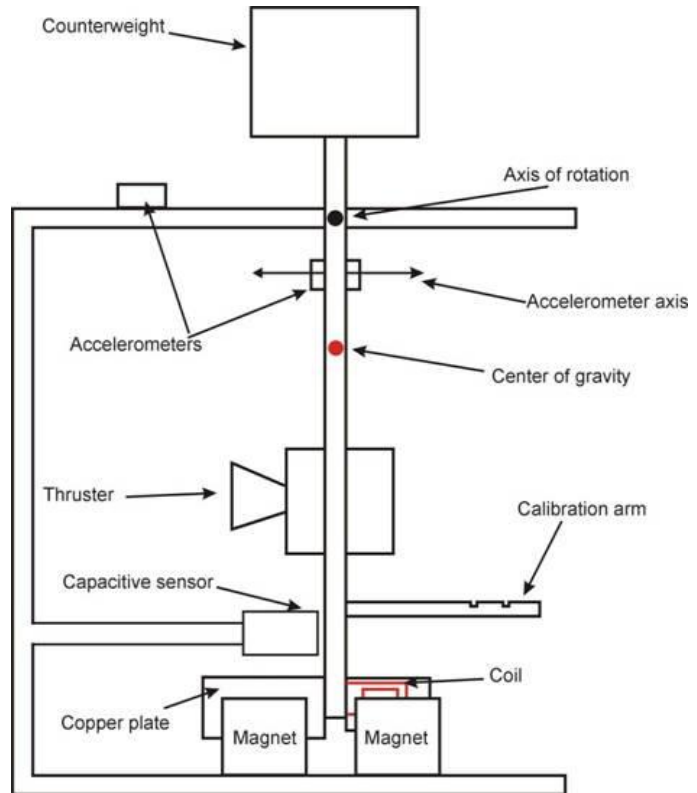


Figure 3. Schematic of the balance.

C. Calibration

1. Calibration of steady thrust

One of the advantages of a pendulum balance is that it allows for an absolute and precise thrust calibration. The principle of calibration for steady thrust is to deposit masses on a small horizontal arm attached to the pendulum (see Figure 4). The masses are deposited using a vertical vacuum-rated translation stage. The calibration can thus be operated in vacuum, in the same exact conditions as the thrust measurements.

The weight of the masses is calibrated very precisely with a Mettler Toledo balance precise to 0.01 mg. Using the notations on Figure 4, the equivalent thrust T_{eq} (in N) for a weight W applied on the arm is $T_{eq} = \frac{D \cdot W}{L}$

If the balance signal is V_{cap} for this weight, then the calibration factor (in V/N) is $C_m = \frac{V_{cap}}{T_{eq}}$.

To check for the linearity over the whole range of measurement, five different masses are deposited sequentially at different positions on the calibration arm (see Table 1).

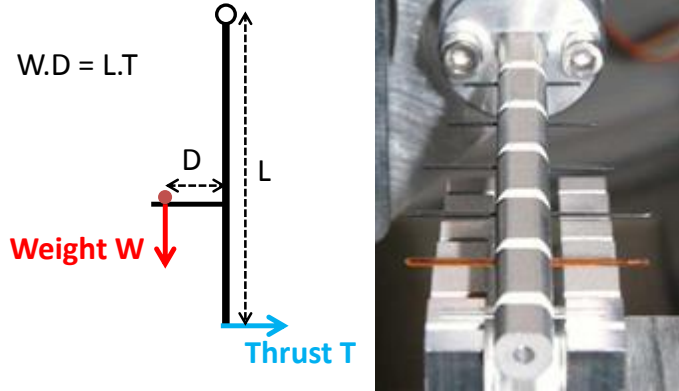


Figure 4. Principle of steady thrust calibration (left) and view of the calibration arm with the masses deposited (right).

	Mass [mg]	Position [mm]	T_{eq} [μ N]
1	6.24	20.5	5.98
2	9.28	25.5	17.02
3	18.70	30.5	43.66
4	45.63	40.5	129.97
5	109.94	45.5	363.62
6	194.75	50.5	822.99

Table 1. Calibration masses and equivalent thrust.

A typical example of thrust calibration is shown in Figure 5 and Figure 6. The calibration coefficient is calculated for each mass. The error bars correspond to the error budget detailed in part II.D. It can be seen that the balance is linear: the calibration coefficient is constant between 6 μ N and 800 μ N.

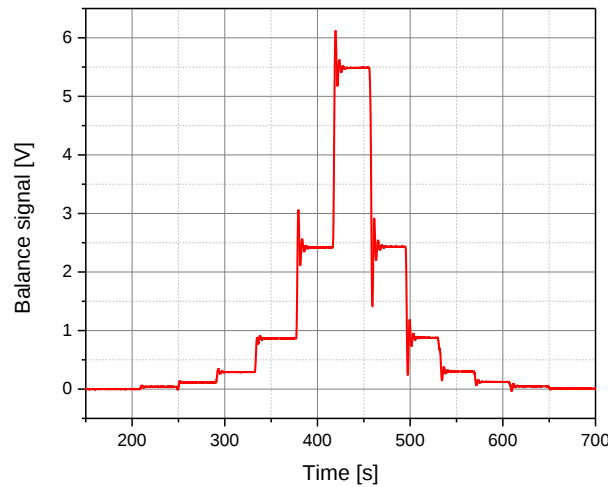


Figure 5. Typical balance signal during steady thrust calibration with the masses.

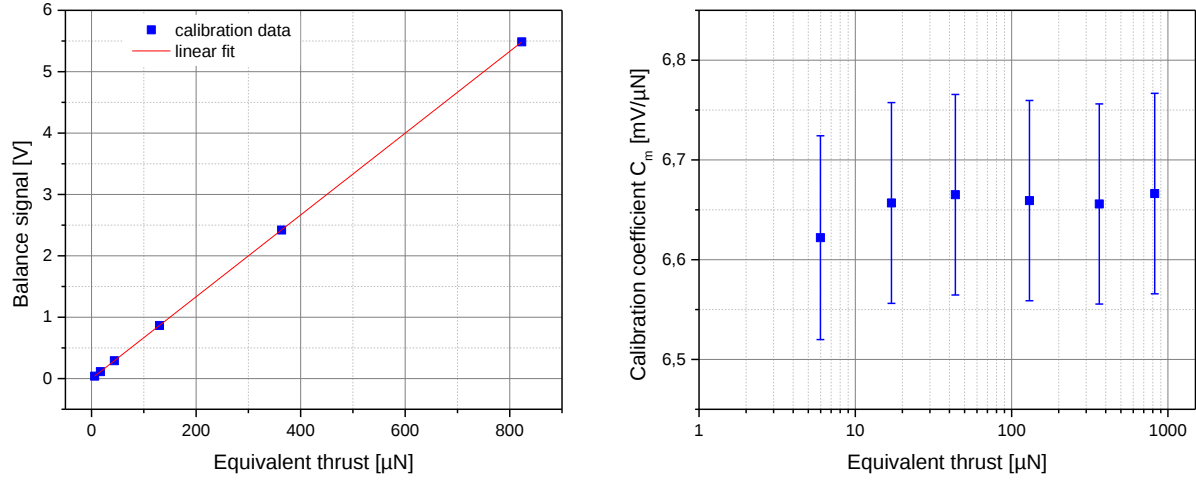


Figure 6. Signal of the balance vs equivalent thrust produced by the mass deposited on the calibration arm and calibration coefficient for steady thrust.

2. Calibration of pulsed thrust

Pulsed thrust calibration is performed with the coil actuator. The principle consists in applying voltage pulses to the coil, and in measuring the balance response. Theoretically, the waveform of the thrust produced by the coil during calibration should be as close as possible to the thrust produced by the VAT (in terms of width and rise time). However, a square pulse is sufficient for pulse calibration, provided that the pulse width is short enough compared to the characteristic response time of the balance, as discussed later in the paper. The amplitude and the width of square pulse are controlled so that calibrated impulse bits are produced.

The first step is to calibrate the coil actuator, i.e. to determine the equivalent thrust that is produced by the actuator for a given current through the coil. Steps of voltage (with a duration of 30s) with different amplitudes V_{coil} are applied, and the balance signal V_{cap} (in V) is recorded. For each pulse amplitude, the coefficient of the coil α is calculated: $\alpha = \frac{V_{cap}}{V_{coil}}$

The voltage amplitude is adjusted in order to produce equivalent thrusts similar to the ones obtained during the calibration with the masses. An example of coil calibration is shown in Figure 7. Since the displacement of the pendulum arm is very low, the force produced the the coil is proportional to the applied voltage, and the coil actuator has a linear behavior.

From the mean values of the calibration coefficient of the balance C_m (in mV/μN) and the coil coefficient α (in V/V), the actuation coefficient of the coil C_{coil} can be calculated: $C_{coil} = \frac{C_m}{\alpha}$

C_{coil} (in mV/μN) represents the voltage that should be applied to the coil to produce an equivalent thrust of 1 μN.

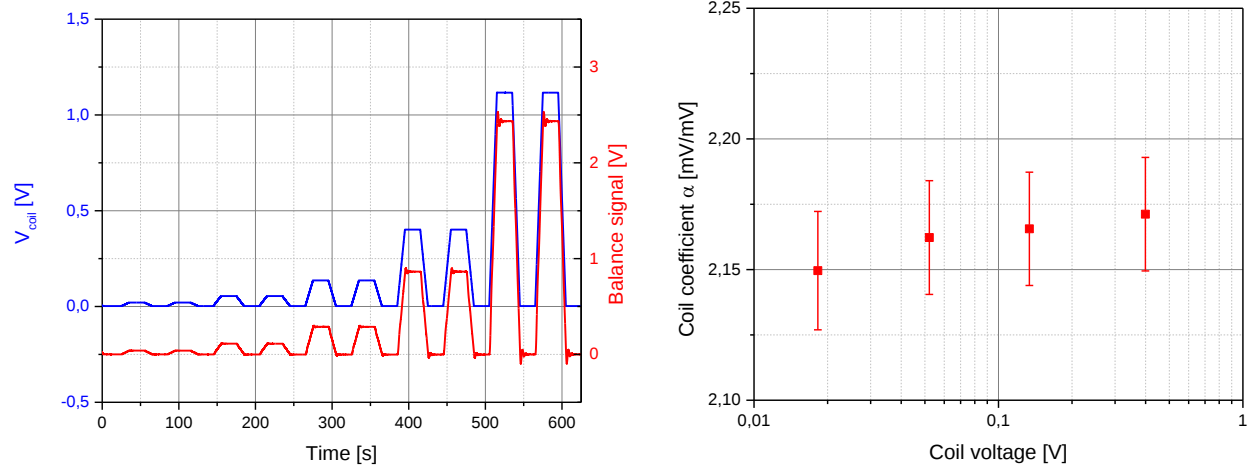


Figure 7. Example of coil calibration for steady thrust.

Square pulses with a known amplitude (2 – 20 V) and width (1 -300 ms) are generated with Quantum 9520 pulse delay generator. The voltage across the coil is recorded to measure precisely the voltage amplitude V_{coil} and the pulse width w_p . The equivalent impulse bit $Ibit_{eq}$ is: $Ibit_{eq} = \frac{w_p \cdot V_{coil}}{C_{coil}}$

An example of the balance signal during the impulse calibration is shown in Figure 8. A square pulse with a width of 200 ms is applied to the coil, producing an pulsed thrust. The amplitude of the first oscillation V_{O1} of the balance signal is used for calibration.

The calibration coefficient of pulsed thrust C_{pulse} is calculated for each equivalent impulse: $C_{pulse} = \frac{V_{O1}}{Ibit_{eq}}$

The value of equivalent impulse is varied by changing the amplitude of the square pulse (from 0.65 V to 6.5 V) with a constant width (100 ms) or by changing the pulse width (from 2 ms to 200 ms) with a constant amplitude (5.3 V). The result of the impulse calibration in Figure 9 indicates that pendulum balance has a linear impulse response between 3.5 $\mu N.s$ and 350 $\mu N.s$. Moreover, the calibration coefficient is the same for both methods, even for the longer pulse width (200 ms).

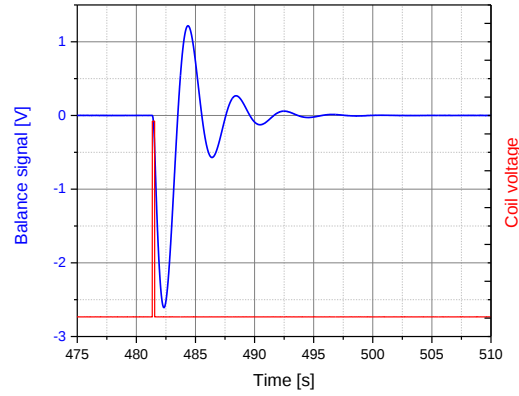


Figure 8. Impulse response of the balance with a square pulse (width: 200 ms) applied to the coil actuator.

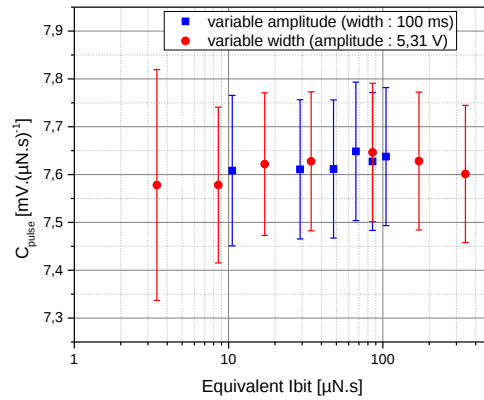


Figure 9. Calibration of pulsed thrust.

D. Error budget

The error budget, as a function of thrust level or impulse bit level, is obtained by evaluating all the sources of error in the measurements. The

different sources of error are detailed in Table 2. The standard deviations of all the terms are added quadratically to obtain the global standard deviation (the terms are assumed independent):

$$\sigma_{T_m} = \sqrt{\sum_1^N \left(\frac{\sigma_{X_i}}{X_i} \right)^2}$$

	Origin	σ_X/X
σ_m	Mass calibration	5×10^{-3}
σ_D	Leverage calibration	10^{-2}
σ_L	Thruster leverage	2.5×10^{-3}
$\sigma_{V_{capa-s}}$	Balance output voltage noise for steady thrust measurements	$\frac{0.13mV}{V_{capa-s}} = \frac{0.013}{T}$
σ_{Ch-s}	Balance hysteresis for steady thrust measurements	10^{-2}
$\sigma_{V_{coil-s}}$	Coil voltage noise for steady thrust calibration	$\frac{5.10^{-3}mV}{V_{coil-s}} = \frac{2.10^{-3}}{T}$
$\sigma_{V_{capa-p}}$	Balance output voltage noise for pulsed thrust measurement	$\frac{0.67mV}{V_{capa-p}} = \frac{0.067mV}{Ibit}$
$\sigma_{V_{coil-p}}$	Coil voltage noise for pulsed thrust calibration	$\frac{1mV}{V_{coil-p}} = \frac{10^{-2}}{Ibit}$
σ_{Ch-p}	Balance output voltage noise and hysteresis for pulsed thrust measurements	5×10^{-3}

Table 2. Error budget of ONERA micronewton balance for mean thrust and pulsed thrust measurements of a vacuum arc thruster.

The error budget for mean thrust and impulse bit measurements are shown in Figure 10. For the thrust, the 1σ uncertainty is about 1.8% in the range of thrust measured in part IV ($T_m > 50 \mu N$). For the Ibit, the 1σ uncertainty is about 2% for Ibit $> 20 \mu N.s$.

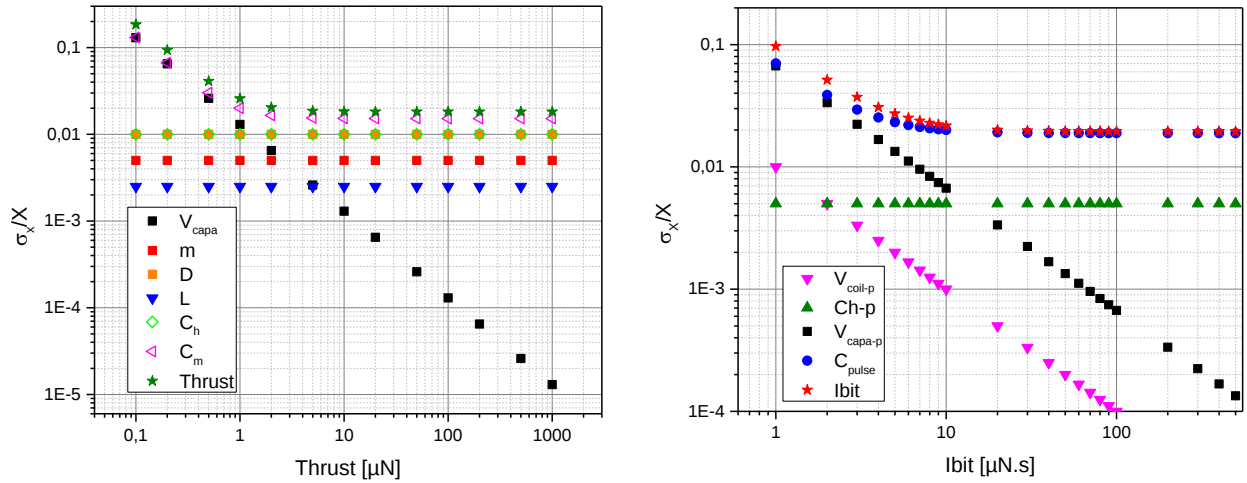


Figure 10. Error budget for mean thrust (left) and impulse bit (right) measurements.

III. Thrust balance model and impulse response

The equation of motion for the pendulum is:

$$J\ddot{\theta} = -Mg r_G \sin(\theta) - c\dot{\theta} + T(t)L\cos(\theta) - k\theta$$

where θ is the angle of deflection of the pendulum, c is the damping coefficient, J is the moment of inertia of the pendulum arm (with the thruster mounted on it), M is the sum of the mass of the arm and the mass of the thruster, r_G is the distance between the axis of rotation and the center of mass, k is the stiffness of the blades, $T(t)$ is the thrust produced by the thruster, and L is the distance between the axis of rotation and the thruster.

With the assumption of very small angles, the equation can be rearranged:

$$\ddot{\theta} + 2\varepsilon\omega_0\dot{\theta} + \omega_0^2\theta = T(t)\frac{L}{J}$$

$$\text{with } \varepsilon = \frac{c}{2J\omega_0} \text{ and } \omega_0 = \sqrt{\frac{Mg r_G + k}{J}}$$

The parameters of the balance are the damping ratio ε , the natural frequency ω_0 , and the static gain defined by:

$$G = \frac{L}{Mg r_G + k}$$

A. Impulse response

The arc phase in the VAT is very small (a few microseconds) compared to characteristic response time of the pendulum (a few seconds). The thrust can then be assumed to be a Dirac delta function: $T(t) = T_0\delta(t)$

Using Laplace transform, the transfer function can be expressed as:

$$G_\theta = \frac{T_0 L}{J} \frac{1}{p - r_1} \frac{1}{p - r_2}$$

$$\text{with } r_{1,2} = \omega_0(-\varepsilon \pm i\sqrt{1 - \varepsilon^2})$$

The impulse response is:

$$\theta(t) = \frac{T_0 L_T}{J\omega_0\sqrt{1 - \varepsilon^2}} e^{-\varepsilon\omega_0 t} \sin\left(\left(\omega_0\sqrt{1 - \varepsilon^2}\right)t\right)$$

The response of the capacitive sensor to an impulse is:

$$V_{cap}(t) = K_{cap} L_{cap} \theta(t)$$

with L_{cap} the distance between the axis of rotation and the capacitive sensor and K_{cap} the sensitivity of the capacitive sensor (in V/m).

B. Response to a square pulse

The previous solution is only valid for very short pulses. During the calibration of the balance for the impulse, square pulse voltage is applied to the coil. Because the voltage supplied by pulse delay generator is limited, a simple solution to extend the range of impulse calibration is to use square pulses with long duration. The model of Dirac function is not valid anymore.

In frequency domain, the step response of the balance ($T(t) = T_0 H(t)$) is:

$$G_\theta = \frac{T_0 L}{J} \frac{1}{p} \frac{1}{p - r_1} \frac{1}{p - r_2}$$

i.e:

$$\theta(t) = \frac{T_0 L_t}{J\omega_0^2} \left(1 - \frac{1}{\sqrt{1 - \varepsilon^2}} e^{-\varepsilon\omega_0 t} \sin\left(\left(\omega_0\sqrt{1 - \varepsilon^2}\right)t + \varphi\right) \right)$$

$$\varphi = \text{atan}\left(\frac{\sqrt{1 - \varepsilon^2}}{\varepsilon}\right)$$

So the response to a square pulse thrust with a width τ and an amplitude T_0 is:

$$\theta(t) = \frac{T_0 L_t}{J\omega_0^2\sqrt{1 - \varepsilon^2}} \left(e^{-\varepsilon\omega_0(t-\tau)} \sin\left(\left(\omega_0\sqrt{1 - \varepsilon^2}\right)(t - \tau) + \varphi\right) - e^{-\varepsilon\omega_0 t} \sin\left(\left(\omega_0\sqrt{1 - \varepsilon^2}\right)t + \varphi\right) \right)$$

The balance signal is simulated is calculated for several pulse widths in Figure 11. The amplitude is adjusted to have a constant impulse bit. The natural frequency is fixed at 0.25 Hz in this test. It can be seen that the amplitude of the first oscillation is significantly reduced when the pulse width is higher than 500 ms, i.e. about 10% of the pseudo

period of the pendulum. This should be accounted for when performing pulse calibration of the balance with the coil actuator.

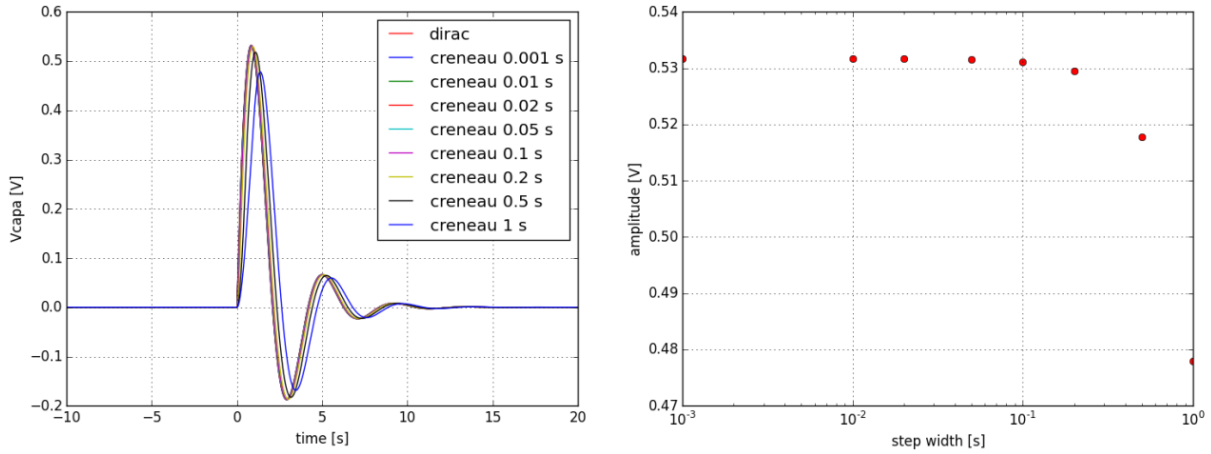


Figure 11. Simulation of the balance signal for a square pulse thrust with different pulse widths.

C. Simulation of the impulse response of the balance

If all parameters of the balance are known, it is possible to simulate the impulse response, as shown in part IIIA. However, because of the uncertainty on some coefficients (damping, stiffness, moment of inertia), it is easier to deduce the balance parameters from measurements.

An example of transfer function of the balance is given in Figure 12. It is obtained with a spectrum analyzer in swept sine mode, connected to the coil actuator. By fitting the experimental data with the theoretical second order transfer function, the natural frequency ω_0 and the damping ratio ε are found. With the balance calibration for steady thrust, the coefficient C_m is determined, and the time evolution of the balance signal can be calculated:

$$C_m = K_{cap} L_{cap} G$$

$$V_{cap}(t) = C_m T_0 \frac{\omega_0}{\sqrt{1 - \varepsilon^2}} e^{-\varepsilon \omega_0 t} \sin\left(\left(\omega_0 \sqrt{1 - \varepsilon^2}\right) t\right)$$

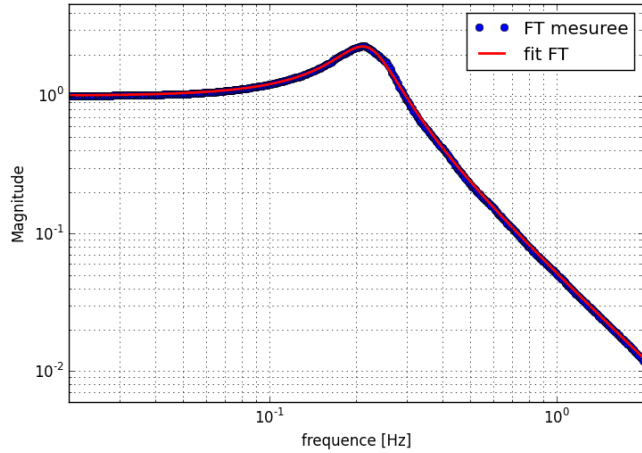


Figure 12. Transfer function of the balance.

In Figure 13, the balance signal (blue line) was recorded during an impulse of 417 $\mu\text{N.s}$ produced by the coil with a 100 ms square pulse. The simulated signal (red line) is calculated using the balance parameters found determined from the transfer function and the steady thrust calibration. No adjustment of parameters was done. It can be seen that the balance signal is properly simulated by this method.

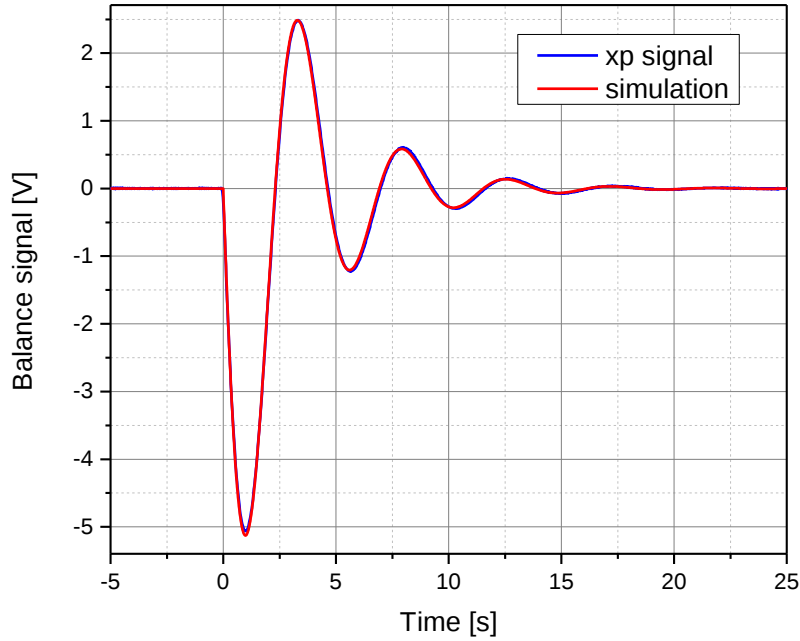


Figure 13. Comparison of the balance signal recorded after an impulse bit and the simulated signal of the capacitive sensor.

IV. Experimental results

The power consumption of PJP thruster is determined from voltage and current measurements on the DC power supply. Voltage is directly recorded on the acquisition board using a voltage divider, while the current is measured with a Hall effect sensor.

A. Mean thrust measurements

The mean thrust produced by PJP thruster is measured for three different pulse repetition frequencies: 2, 5, and 10 Hz. Steps of thrust of 30 s, with a 100 s inter-step delay, are generated. The steps are shown on Figure 14. Five steps are generated for each frequency. For mean thrust measurements, in order to reduce the noise, the signal of the capacitive sensor is post-processed using a moving average that reduces the bandwidth to 0.4 Hz. The sensor signal is detrended in order to remove the thermal drift, and converted to thrust using the calibration coefficient of the balance C_m . No other post-processing method is used.

For each thrust step, the impulse bit I_{bit} and the thrust to power ratio TTPR are calculated from the mean thrust value T_m :

$$I_{bit} = \frac{T_m}{f_{VAT}}$$

$$TTPR = \frac{T_m}{P_m}$$

where f_{VAT} is the repetition frequency of the discharges in VAT thruster and P_m is the mean power consumption of the thruster during the step. It should be noted that P_m is measured on the DC generator, so the TTPR includes the efficiency of onboard electronics.

The performances of PJP thruster are summarized in Figure 15. Thrust values are between 57 μN (at 2 Hz) and 288 μN (at 10 Hz). It can be seen that the impulse bit is constant with the pulse repetition frequency. The dispersion of results is well within the 3σ uncertainty of the error budget. The mean I_{bit} can be inferred from the linear fit of mean thrust vs repetition frequency: 28.7 $\mu\text{N.s}$.

TTPR tends to increase with frequency: from 6.6 $\mu\text{N.s}$ at 2 Hz to 8.8 $\mu\text{N.s}$ at 10 Hz. However, if one takes into account only the power used for charge of the capacitors, TTPR is almost constant with frequency, with a mean value of 9.3 $\mu\text{N/W}$.

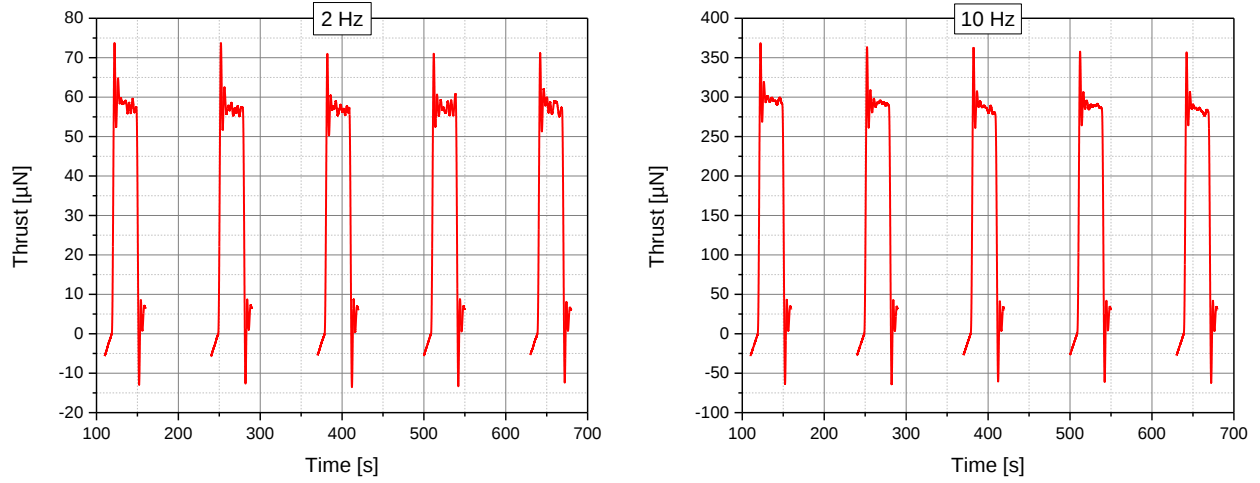


Figure 14. Steps of thrust measured on VAT thruster with pulse repetition frequency of 2 Hz and 10 Hz.

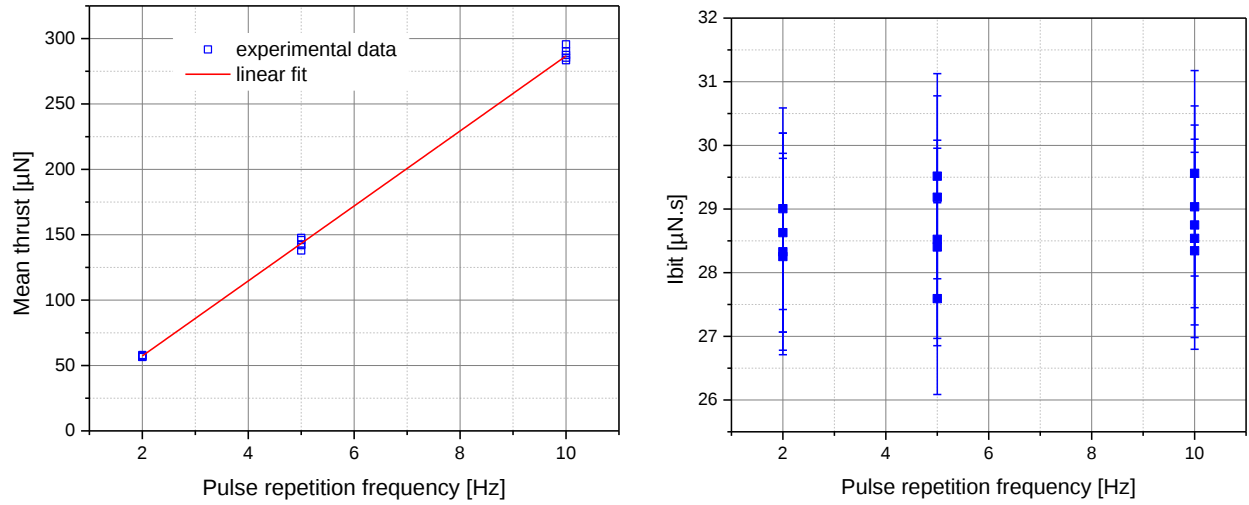


Figure 15. Mean thrust and impulse bit vs pulse repetition frequency. The five steps produced during the measurements are plotted. The error bars correspond to 3σ error budget.

B. Ibit measurements

The thrust impulse $Ibit_{mes}$ is deduced from the amplitude of the first oscillation of the balance signal:

$$Ibit_{mes} = C_{pulse} \cdot V_{o1}$$

An example of balance signal and of power consumption by the thruster during a single discharge is given in Figure 16. The energy per pulse is obtained by integrating the power consumption over the pulse duration.

The distribution of impulse bits over 120 discharges is shown in Figure 17. The error bars for Ibit correspond to 1σ uncertainty of the error budget, while the error bars on the energy correspond to the uncertainties due to the noise on DC voltage and current measurements. Most of the impulses are around a mean value of 29 $\mu\text{N.s}$.

The statistics on Ibit and energy per pulse are given in Table 3. The mean value of Ibit over the 120 single discharges is $29.2 \mu\text{N.s} \pm 1.8 \mu\text{N.s}$. This value is in line with the impulse bit inferred from mean thrust measurements ($28.7 \mu\text{N.s}$)

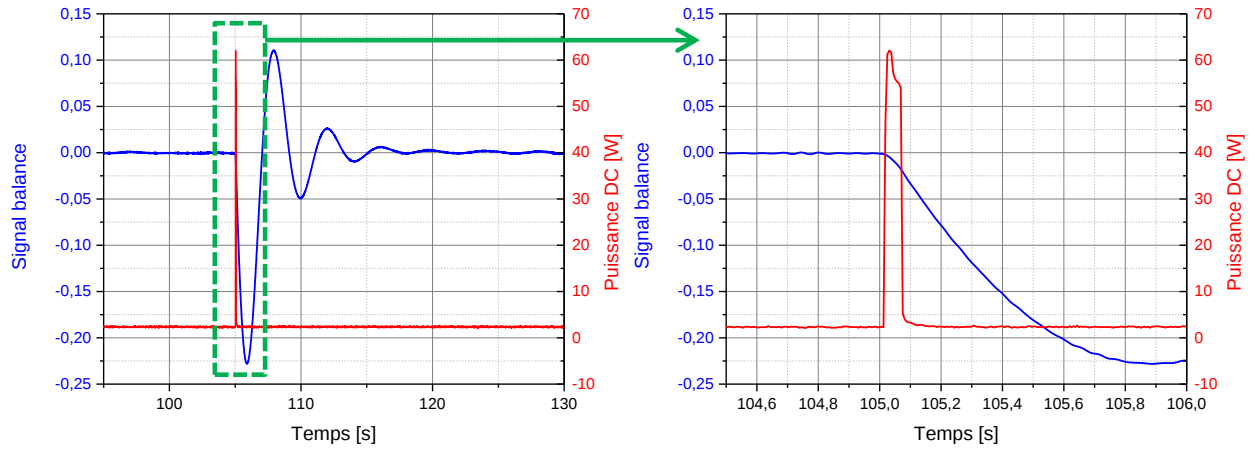


Figure 16. Example of balance signal and DC power recorded during a single impulse produced by the VAT thruster

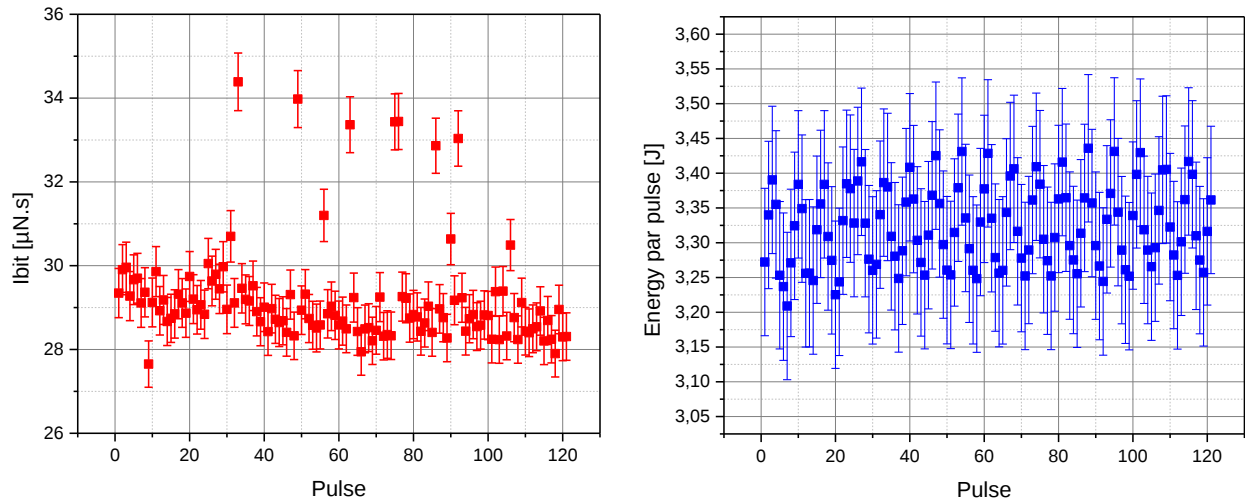


Figure 17. Distribution of impulse bit and energy per pulse measured for 120 discharges of VAT thruster. The error bars on Ibit and energy correspond to 1σ and 3σ uncertainty, respectively.

	Ibit	E_{pulse}	Ibit/ E_{pulse}
Mean value	$29.2 \mu\text{N.s}$	3.32 J	$8.79 \mu\text{N.s/J}$
Standard deviation	$1.2 \mu\text{N.s}$	0.06 J	$0.41 \mu\text{N.s/J}$
Relative standard deviation	4.1%	1.7%	4.7%

Table 3. Summary of impulse bit measurements. The energy per pulse is directly measured on the DC power supply, and includes the losses of onboard electronics.

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