Endurance testing of a pulsed plasma thruster for nanosatellites

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A B S T R A C T

The mission complexity of Nanosatellites has increased tremendously in recent years, but their mission range is limited due to the lack of an active orbit control or Δv capability. Pulsed Plasma Thrusters (PPT), featuring structural simplicity and very low power consumption are a prime candidate for such applications. However, the required miniaturization of standard PPTs and the adaption to the low power consumption is not straightforward. Most investigated systems have failed to show the required lifetime. The present coaxial design has shown a lifetime of up to 1 million discharges at discharge energies of 1.8 J in previous studies. The present paper focuses on performance characterizations of this design. For this purpose direct thrust measurements with a μN thrust balance were conducted. Thrust measurements in conjunction with mass bit determination allowed a comprehensive assessment. Based on those measurements the present μPPT has a total impulses capability of approximately \( I \approx 1.7 \text{ Ns} \), an average mass bit of \( 0.37 \mu \text{g s}^{-1} \) and an average specific impulse of \( I_{sp} \approx 904 \text{ s} \). All tests have shown very good EM compatibility of the PPT with the electronics of the flight-like printed circuit board. Consequently, a complete μPPT unit can provide a Δv change of 5.1 m/s or 2.6 m/s to a standard 1-unit or 2-unit CubeSat respectively.

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1. Introduction

The recent success of CubeSats allows the definition of advanced mission concepts, having CubeSats employed in advanced scientific applications, including formation flying [1,2]. However, the enabling technology for such missions, namely autonomous propulsion and active attitude control with high pointing accuracy remains elusive [3,4]. This originates from the difficulties of miniaturizing existing propulsion concepts either regarding structural–mechanical limits in the case of chemical propulsion, or too stringent power limitations for many types of electric propulsion [5].

Currently there are various efforts in miniaturizing propulsion technologies appropriate for the size of CubeSats, including cold gas thrusters based on both gaseous (CanX-2) [6,7] and solidified propellant (Delfi-n3Xt) [8] and electrical propulsion systems, such as vacuum arc thrusters (ION) [9] and Field Emission based ion thruster (FEEP) [10].

Another electrical type of thruster which lends itself well to miniaturization is the structurally simple pulsed plasma thruster (PPT), which is operated in pulsed mode, adapting well to low power available. Thanks to their ability to deliver small impulse bits and their high reliability, miniaturized PPTs (μPPTs) are well suited to enable precise formation flying. Furthermore, pointing accuracies currently only obtainable by reaction wheels are expected, which could therefore considerably reduce mass and power requirements for high performance stabilization [11]. An additional system benefit of PPTs is the quasi-neutrality...
of the expelled plasma, making the need for charge neutralization obsolete.

PPTs were first flown in space on the Soviet Zond-2 mission [12]. Ever since then, PPTs have been employed in various space missions [13], with utilization reaching from orbit insertion and drag make-up (TIP/NOVA with a total of 28 thrusters) to east-west station keeping (LES-6) [14] to active attitude control (SMS and LES-8/9) [15,16]. Typical discharge energy levels of flight experienced PPTs range from a few joules (LES-6, SMS) to one hundred joules (EO-1, MightySat-II) [17–19].

Presently, several research teams focus on the investigation of μPPTs [20,21], but none has shown the reliability and lifetime necessary for such application. The investigation presented in the following has focused on μPPT performance evaluation during long term employment, similar to future employments on CubeSats. Fig. 1 shows the plasma plume of the coaxial μPPT design investigated in this work. With the available resources no further characterization of the plume, especially the divergence angle, could be performed.

2. Operation principle

The PPT is an electro-dynamic thruster, accelerating ionized propellant by interaction of the electric current in the plasma and the self-induced electromagnetic fields [22]. In an annular coaxial design, shown in Fig. 2, the acceleration chamber consists of two concentric, tubular shaped electrodes made of copper with the propellant TEFLO®N in between. The external diameter of the PPT is roughly 9 mm and its length is 35 mm. The diameters of the concentric electrodes are 6.0 mm and 4.8 mm respectively. With the total propellant area of 10.2 mm² and the total weight of only 15 g, even 2-unit CubeSats can easily be equipped with multiple PPTs in order to allow sophisticated attitude control and formation flight maneuvers. The PPT head was designed and manufactured at FOTEC and is optimized for low mass and volume, low discharge energy and good electro-magnetic compatibility. A high voltage capacitor, used to store the discharge energy for one pulse, is connected to the electrodes. While the plasma acceleration process is a highly complex physical matter [23–27], simple models are available to guide the preliminary thruster design [28–35]. The size of the complete thruster module including four PPT heads, high voltage capacitors shared between the individual μPPT heads, igniters and conditioning electronics is 90 × 90 × 30 mm³. Total weight of the unit is about 300 g with the capacitors being the major driver of the weight. The usage of custom-made peak current optimized capacitors, significant weight reduction is expected for future revisions. The igniter is introduced annularly into the acceleration chamber through the TEFLO®N propellant. The igniter triggers the main discharge, featuring peak current values

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up to 3 kA, which then ablates, dissociates, ionizes and accelerates the propellant.

In Fig. 3 the typical current pulse during discharge is shown for standard-shape μPPT with different width-to-gap aspect ratios. Due to the encapsulated μPPT design and its fixed assembly on the PCB, the discharge characteristics could not be determined in the scope of this work, but because of similar geometric dimensions and the same electrical setup, similar results can be expected.

3. Thrust balance

3.1. A. Balance description

In order to determine the generated thrust of the μPPT, a μN torsion balance has been set up. The operational balance set up in the vacuum chamber is shown in Fig. 4. The system is comprised of a horizontal Aluminum beam with a total length of 70 cm which is suspended by two stainless steel spring bearings manufactured by C-Flex with a spring rate of 0.2 Nm/rad per bearing (not visible). In the front of the picture one of the two 12 × 12 cm² tables can be recognized which are directly mounted on the beam—one for the thruster module and the other one for the corresponding counterweight. The displacement of the beam is measured using a high-precision optical distance transducer mini DMS manufactured by Philtec. The oscillation frequency of the system is measured and knowing the torques of inertia of the arm and the tables, the exact spring rate can be computed which is required to determine the generated thrust of the μPPT. To account for the low damping of the beam which in vacuum is only caused by friction of the bearings, a passive magnetic eddy current brake has been implemented to lower the measurement noise and oscillations (in the foreground just below the table the disc-shaped magnet can be recognized).

The time-averaged thrust transferred to the torsion balance by the μPPT, with thrust axis oriented perpendicular to the balance beam at distant r = 29 cm from the pivot, can be expressed as a function of angular deviation θ

\[
\bar{T} = \frac{\bar{d} \kappa}{r}.
\]  

(1)

Ref. [36] gives a comprehensive derivation of this relation from the general second-order differential equation for the torsion balances and damping systems and discusses the justification of averaging the measured parameters for the given configuration.

Since Eq. (1) is dependent on the spring rate κ, which might be subjected to thermal drift, the balance was additionally equipped with an electrostatic comb structure, allowing alternative thrust measurements independent of material parameters. Therefore, the generated thrust by the μPPT is compensated by applying an anti-parallel force of the same strength using the comb structure. According to Ref. [36], the thrust from the μPPT can be expressed as function of the applied comb structure voltage difference U

\[
T = \frac{1}{2} \varepsilon_0 n \frac{b}{d} \frac{l_c}{T} U^2
\]  

(2)

The reflective displacement transducer and the static comb structure have been identified as critical parts of the balance with respect to high sensitive thrust measurement.
Therefore, proper performance of these crucial components has been validated. The accurate operation of the reflective displacement transducer was verified with the aid of a Keyence LC-2400W laser displacement meter. No malfunction or unexpected deviations have been detected. In addition, magnetic deflection has been used to validate the electrostatic comb structure since only small direct currents are used and no high voltage is needed which may be a potential source of measurement errors due to unmeant static charging.

3.2. B. Balance accuracy

The optical displacement sensor uncertainty was determined using a mirror at mechanically fixed distance to the sensor face. The resulting measurement noise and drift of the reflective displacement sensor and the measurement electronics are listed in Table 1. The noise and drift of the overall, fully equipped, thrust balance was determined at vacuum operation conditions for a chamber pressure below $5 \times 10^{-7}$ mbar after 48 h in vacuum conditions in order to achieve thermal equilibrium and to rule out outgassing effects.

The balance response time was determined by applying a step force of 100 $\mu$N to the fully equipped thrust balance using the electrostatic comb. The response time, defined as the time elapsed from 10% to 90% of the final deflection was found to be 1.6 s. The natural frequency of the balance is therefore 0.6 Hz but it strongly depends on the weights put on the tables.

4. Test facility and balance operation

For thrust measurements, the $\mu$PPTs were pulsed at three different frequencies of 1/3 Hz, 1/6 Hz and 1/9 Hz (or alternatively 1 Hz, 1/2 Hz and 1/4 Hz), resembling the operation conditions for limited power budgets when employed in CubeSats. An operation time of 60 s was found to be long enough to compute a reliable value of the average thrust. To account for the thermal drift of the thrust balance which results in a drift rate as given in Table 1, that distorts the measurement results when used over a long-term interval, the deflection is measured before and after the $\mu$PPT operation for 60 s when kept idle. Fig. 5 shows a section of a thrust measurement at the discharge energy of 1.82 J where the $\mu$PPT is kept idle for 60 s and then pulsed at 1/3 Hz for 120 s. The generated mean thrust is indicated based on an averaging interval of 3 s. The recorded thrust signal shows constant thrust levels throughout the entire firing period, without any noticeable influences caused by initial thermal disequilibrium and thus justifies the choice of measurement intervals of 60 s. Due to the inertia of the thrust balance and the aforementioned natural frequency of 0.6 Hz, the arm does not return to its initial position between the pulses.

The corrected thrust is then given by

$$T_{\text{corr}} = T - \frac{T_{\text{before}} + T_{\text{after}}}{2},$$

with the subscripts “before” and “after” referring to the measurements periods in which the thruster is kept idle.

5. Thrust measurement of a miniaturized coaxial thruster

The coaxial type ablative $\mu$PPT design offers favorable mechanical properties, since the outer electrode fully confines the propellant and the plasma and thus acts as a shielding barrier protecting the surrounding structure, making additional shielding, which can cause leakage current when covered with carbon, obsolete. For energy storage, two capacitors of 1 $\mu$F each were charged to 1350 V. A mockup of the module containing the PPU and four thrusters is shown in Fig. 6, with potential application shown on the right hand side. Each of the $\mu$PPTs on the module is equipped with a dedicated igniter circuit, allowing for individual control of each thruster.

![Fig. 5. Typical thrust measurement sequence of a $\mu$PPT.](image)
Fig. 7 shows the direct thrust measurements for three different firing frequencies, each repeated three times, and the resulting mean impulse bit measured as a function of the discharge energy. Three different discharge energies were tested by varying the capacitor charging voltage. As can be seen, in this energy and discharge frequency range, the impulse bit determination is independent from discharge frequency, only showing minor effects of increased thermal load for increased firing frequencies. The bars indicate the deviation between the single measurements and do not correspond to the total thrust measurement error. Further measurements will be necessary in order to determine the temperature increase of the PPT head for various ignition frequencies.

5.1. A. Lifetime thrust measurement

Lifetime tests have been performed using a coaxial type μPPT incorporated into the PPU module. The entire thruster module was mounted on the balance and fired at 1/3 Hz continuously to simulate CubeSat operational conditions with an average power consumption of less than 1 W.

Thrust measurements using the test procedure described before were conducted at intervals of 2 h, or approximately 2400 ignitions. A long duration test including thrust measurement was conducted for a total of $4.2 \times 10^5$ discharges. The resulting impulse bit measured as function of the number of ignitions is shown in Fig. 8.

To avoid the increasing complexity of a moving propellant in the highly miniaturized design employed, the propellant was not repositioned as in the case of standard PPT designs, in which the propellant front face position is kept constant. Therefore, ablation of the propellant leads to recession of the propellant face relative to the thruster electrodes, prolonging the acceleration chamber. The degradation of thrust as already been observed in previous designs [42] is traced back to this recession of propellant. The accumulated impulse delivered by the thruster was determined to $I = 1.7 \text{ Ns}$ for $4.2 \times 10^5$ discharges. Assuming a standard 1-unit CubeSat with a maximum mass of 1.33 kg, a propulsion unit containing four thruster heads would be able to deliver a $\Delta v$ change of $\Delta v \approx 5.1 \text{ m/s}$, enabling drag make-up maneuvers, formation flight and constellation maintenance [37–41]. In a realistic scenario concerning volume and power budgets available, the thruster module will most likely be employed in a 2- or 3-unit CubeSat architecture, with accordingly reduced velocity changes delivered to the satellite of $\Delta v \approx 2.6 \text{ m/s}$ or $\Delta v \approx 1.7 \text{ m/s}$ respectively, again assuming a mass of 1.33 kg per CubeSat unit. However, long duration tests performed without thrust measurements showed successful thruster operation up to $10^3$ discharges, therefore significantly increasing the total impulse per thruster and the corresponding $\Delta v$ change.
The specific impulse measured is found in the lower region of range of specific impulse expected for this type of thruster which is anticipated considering the given miniaturization and low energy operation [44]. This translates directly, using a time-averaged mass bit given in Fig. 9 and basic energy relations, into an initial efficiency of $\sim 3.9\%$ which decays to 1.1% after 100,000 ignitions and reaches lower values of 0.7% after succeeding 3,000,000 ignitions. These values are located near the lower end of expected efficiency range for this type of thruster.

6. Conclusion

The pulsed plasma thruster is a candidate propulsion technology for miniaturization to meet the stringent requirements posed by nanosatellites. These miniaturization requirements especially pose difficulties regarding the reliability and lifetime of such miniaturized thrusters. The current paper presents a highly miniaturized pulsed plasma thruster in recessive ablative coaxial configuration for low power operation. The thruster was characterized and its performance in long duration tests was manufactured in-house and investigated. The thruster was incorporated in a fully operational propulsion unit containing the PPU and up to four thrusters, and thrust was measured throughout a period of $4.2 \times 10^5$ ignitions. Direct thrust measurement of the thruster was performed using a dedicated thrust balance, able to resolve $\mu N$ forces. Total impulses delivered throughout the lifetime test were determined to be $I_{\text{bit}} \approx 1.7 \text{ N sr}$ one thruster. For the miniaturized thruster module presented, which comprises four thrusters, this amounts to a $\Delta v$ change, based on a 1-unit CubeSat, of $\Delta v \approx 5.1 \text{ m/s}$, and correspondingly decreased values of $\Delta v \approx 2.6 \text{ m/s}$ and $\Delta v \approx 1.7 \text{ m/s}$ for 2-unit and 3-unit CubeSats respectively, based on a satellite mass of 1.33 kg per CubeSat unit. Minimum discrete impulse bits, necessary for fine attitude control, were measured to $I_{\text{bit}} \approx 10 \mu \text{N s}$, decreasing to $I_{\text{bit}} \approx 3.5 \mu \text{N s}$ for increased operational lifetime.

Long duration mass bit measurement was performed over the test duration of $6.9 \times 10^5$ ignitions. This test showed degradation in mass bit with increasing total number of discharges corresponding to impulse bit degradation. The combined data allowed for an estimate of the achieved specific impulse over the entire test period of $I_p = 904 \pm 212$ s for the low power, miniaturized thruster configuration.

The thruster module described and used for testing in this paper allows the individual control of each of the four thrusters, using four separate ignition circuits, allowing for individual change on discharge frequency and thus thrust produced. The ability to individually address each thruster allows for flexible control in case of thrust deviation of a single thruster head by modifying the discharge frequency of such a thruster, maintaining a uniform thrust, if necessary. The discharge frequencies achieved by the four thrusters within the module will be limited by the power budget delivered by the CubeSat only.

The $\mu$PPT presented and investigated in this work is therefore found capable of providing reliable autonomous

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**Fig. 8.** Long duration thrust measurement of $\mu$PPT.

**Fig. 9.** Long-term mass bit measurement of $\mu$PPT.

Disassembly of the TEFLON® propellant bar for weight measurements and mass bit determination respectively was not possible due to the fashion the $\mu$PPT is assembled within the propulsion module. Therefore, mass bit determination was performed in a separate long duration test for an identical $\mu$PPT without direct attachment of the $\mu$PPT to the PPU module, allowing easy disassembling and weight determination of the propellant. This method improved the accuracy of the measurement compared to past results [43]. In this configuration, mass bit determination was performed by gravimetric weight determination of the propellant before and after the test interval. All weight measurements have been conducted after storage of the propellant under ambient conditions for 24 h to account for atmospheric humidity intake. The resulting mass bit values (shown in Fig. 9) are therefore mean values averaged over the number of discharges of the determination interval. As in the case of the impulse bit, the recess of the propellant surface leads to a degradation of the mass bit. Although the different ways of connecting the $\mu$PPT to the PPU in the case of thrust and mass bit measurements introduce an unknown error in the electrical circuit parameters of the system, the combination of the data presented in Figs. 8 and 9 allows an estimation of the average specific impulse achieved for the $\mu$PPT configuration employed. The mean specific impulse averaged over $4.2 \times 10^5$ discharges becomes $I_p = 904 \pm 212$ s.

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The $\mu$PPT presented and investigated in this work is therefore found capable of providing reliable autonomous
propulsion for Nanosatellites, potentially increasing the satellites mission performance.

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