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研究課題名（和文）Air-Breathing Pulsed Plasma Thruster

研究課題名（英文）Air-Breathing Pulsed Plasma Thruster

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研究成果の概要（和文）：地球低軌道を回る人工衛星の寿命を延長するため新しい推進コンセプトを考えた。大気吸込式電気推進とは低軌道に薄く残留してある大気を推進剤として利用する推進方法である。本研究ではそのコンセプトの実現可能性を調べるため、実際の衛星運転時の状況を最大限に再現して、空気供給システム・推進器・性能測定装置で実験を行った。更に初期運転時の性能特性結果を分析し推進器と空気供給システムの構造を改善した。

研究成果の概要（英文）：In order to extend the mission lifetime of satellites in lower Earth orbits, a new propulsion concept was conceived. By using the residual atmosphere on orbit as propellant, a new propulsion concept is found and named air-breathing electric propulsion. In this research, the feasibility of the concept was investigated by conducting experiments at conditions close to such a propulsion system. Therefore an air-feeding propellant management system, a new thruster and performance evaluation equipment had been set up and experiments conducted. With the results of the performance during initial operation, the thruster and the feeding system were improved in design.

研究分野：電気推進器

キーワード：パルス型プラズマスラスター　電気推進器　大気吸込式

１．研究開始当初の背景

Recent years saw an increased interest in pushing the frontiers of electric propulsion application in space in many directions: higher power, miniaturization, deep space, lower Earth orbits, and so on. The latter is attributed to the fact that most satellites without propulsion would quickly lose altitude due to the residual atmosphere’s drag in orbits below 200-300 km of altitude. As the propellant consumption of a long-term operation would be staggeringly high, few missions are considered to remain in these low orbits and can do so only by enormous effort put in both the satellite design and the propulsion development.
The scientific interest is higher for lower orbits down to 100 km of altitude as the gradients in the atmospheric properties are yet to be investigated, and the closer proximity to the Earth’s surface would allow for a better observation of natural and man-made processes.
A common approach to overcome the issue of the high propellant consumption is the usage of the residual atmospheric gases as propellant in any of the many kinds of electric propulsion. In fact, the idea to do so dates back many years, but it was only until recently that practical work could be undertaken to verify whether the vision could become true. Although electrostatic propulsion, in the form of ion thrusters and Hall effect thrusters, were successfully operated with atmosphere-like propellants, the performance naturally dropped, but it also revealed that the power consumption increased as ionization became more energy-consuming.
Consequently, we proposed to use pulsed plasma thruster technology as an alternative as performance drop and erosion issues seem to be of a lesser concern.

２．研究の目的

The major objective of this work was to verify the usefulness of the PPT proposal, and to demonstrate that an air-breathing PPT would be a viable alternative to be considered.
As the previous thruster operated at too low a discharge energy to be sufficiently efficient and to make changes in the thrust performance observable, this study also aimed at a new design of the thruster head, and the necessary changes on the thrust balance to measure the higher-energy PPT. Eventually, we wanted to demonstrate the feasibility of an air-breathing PPT concept and identify design criteria for next thruster generations.

３．研究の方法

To evaluate the performance of an air-breathing system, a new thruster was set up that could be used with various propellants allowing for a comparison and a detection of weaknesses and points for improvement. Additionally, a propellant feeding system for gaseous propellant was set up including pressure gauges and solenoid valves to be able to adjust the flow to the discharge.
The PPT used in this study comprises of a 15 μF capacitor with a rated nominal voltage of 2500 V, a pair of parallel copper electrodes with a shape for higher electromagnetic acceleration, and a high-voltage vacuum discharge igniter. The resistance and inductance of the circuit were kept small in the design to reduce losses in the discharge. The CAD model of the PPT with the gaseous propellant feeding is shown in Fig. 1.

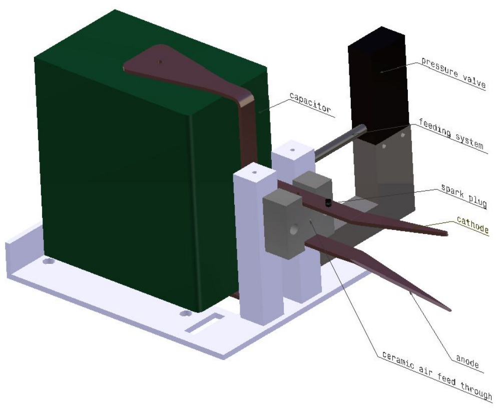

Figure 1: Schematic of PPT and feeding system

The experiments were conducted in a ⌀1 m x L1.5 m vacuum chamber equipped with a rotary pump and a turbo-molecular pump reaching an ultimate pressure of 5 x 10^{-5} mbar prior to pulse operation.
Discharge properties were recorded with a differential voltage probe and a high-sensitivity low-noise Rogowski current probe.
A thrust balance was established in the vacuum chamber to be able to measure the

expected impulses of less than 1 mNs. A new calibration method was set up, and extensive testing of the measurement system conducted to improve the sensitivity and assure best possible accuracy in the eventual performance measurement. The thrust balance schematic is shown in Fig. 2.

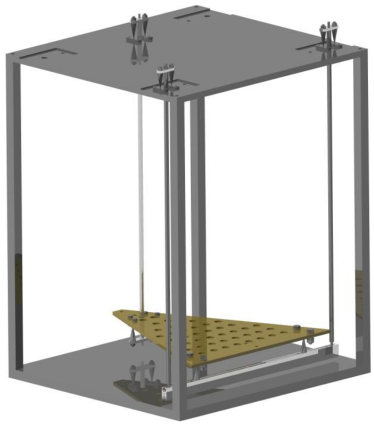

Figure 2: Schematic of thrust balance

4．研究成果

The propellant feeding system was set up and tested first with the previous thruster model. The computer procedures to handle the injection of air and the ignition of the thruster were established and successfully tested. An air-supported discharge was achieved as shown in Fig. 3.

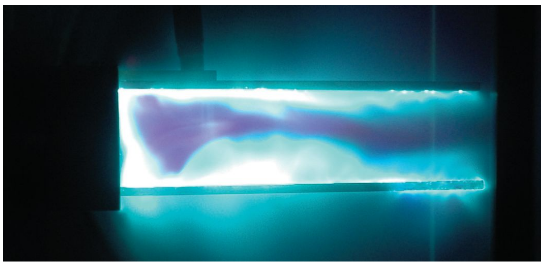

Figure 3: PPT discharge with air injection

This essentially showed that operation of a PPT with air as propellant is feasible. With the setup of the thrust balance and the new PPT thruster model, a more thorough experimental investigation was possible. To evaluate whether air as propellant shows similar performance to other propellants, solid PTFE (Teflon) and liquid PFPE (Krytox, Fomblin) were tested and evaluated concurrently. Discharge current profiles at maximum capacitor energy are shown in Fig. 4.

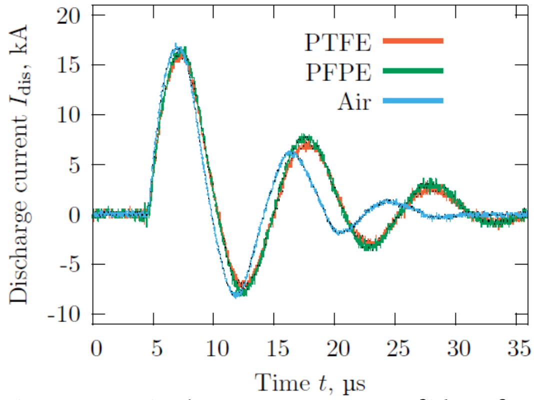

Figure 4: Discharge current profiles for various propellants

The results again prove that air was successfully consumed in the discharge, and that the new PPT is also capable to operate in an air-supported discharge mode. Calibrated performance evaluation was conducted and the impulses of the various propellants consumed in the discharge recorded. Additionally, the impulse of the gas injection itself was recorded to evaluate the effectiveness of the discharge for the thrust generation with air. The result of this cold gas test together with the propellant performances are plotted against discharge energy in Fig. 5.

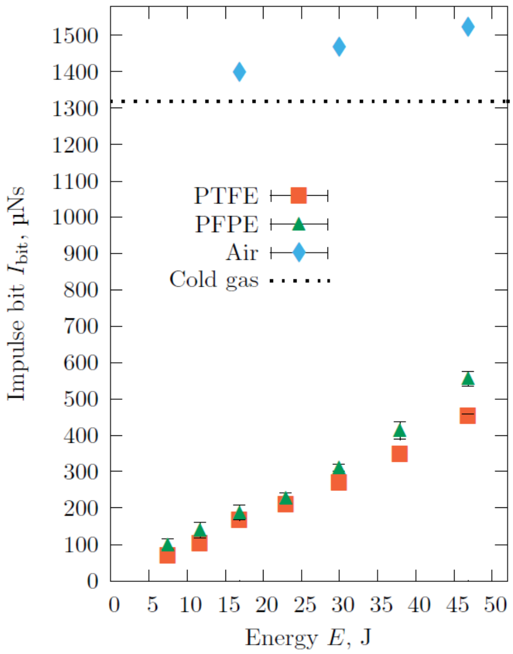

Figure 5: Thrust impulse measurement results for various propellants and discharge energy levels

The results indicate that the gas injection is too powerful in comparison

with the thruster as the cold gas flow pulse is significantly stronger than the discharges in the thruster when using solid or liquid propellant. Adding discharge energy to the injected air does increase the impulse, showing that PPT operation is feasible. However, the gain is smaller compared to the other propellants.
Further, in the operation with air, it was observed during the discharge, that air was spreading in all directions prior to the discharge, and thus not contributing much to the directed thrust.
Two design aspects were identified to enable a better operation. Firstly, the pressure in the propellant feeding is too high and would cause too much mass per pulse to be injected leaving at too high velocity for the discharge to consume it. Therefore, an improvement of the propellant feeding system was started within this study and will be continues in the continued work.
Secondly, the design of the PPT was seen as not suitable for an optimum air operation as the injected propellant would spread in all directions. A coaxial design was conceived and a new thruster head designed and built to evaluate this hypothesis. The design is shown in Fig. 6.

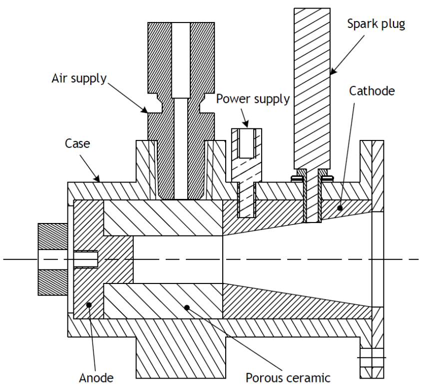

Figure 6: New coaxial design for optimized air performance

Testing of the new design was started prior to the end of this study, but thorough evaluation is ongoing, and will be conducted in the continued work. Indications, however, show that a much better performance can be expected which will be combined with the improved propellant feeding system to provide the world’s first air-operating PPT that will be used in future research and development efforts towards an atmosphere-breathing system.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔学会発表〕（計　3 件）

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６．研究組織

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