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Attitude Testing Platform in a Vacuum Environment for a Lean Satellite with an Electric Thruster

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Abstract

Air-bearing tables are widely used for the verification of attitude control systems (ACS) based on reaction wheels (RW) and/or magnetic actuation. There is a demand for testing ACS based on electric propulsion systems (EPS) for lean (small) satellites. However, traditional air-bearing platforms cannot be used for such verification, since the test conditions require a vacuum environment. To address this problem, the current work presents the development of an attitude testing platform for lean satellites capable of working in a high vacuum environment, that can be used to verify ACS based on electric thrusters such as vacuum arc thrusters (VAT) and pulsed plasma thrusters (PPT). A testing platform with a spherical air bearing that allows a frictionless, rotational motion on three rotational degrees of freedom was placed inside a vacuum chamber equipped with a rotary pump and cryogenic pump. The vacuum achieved 2.4×10^{-2} Pa as pressure inside the chamber, while the platform was lifted by dry air with a 40-sccm flow rate. The instrumentation of the testing platform included an onboard control unit, a gyroscope sensor for the measurement of the platform angular rate, and an RW and a VAT as actuators that provide a controlled rotational motion. The response of the platform's angular rate under the controlled actuation of the RW and VAT was evaluated. Once the operation of the VAT inside the vacuum chamber was confirmed, the induced rotation speed by ignitions from the VAT was measured, to derive the VAT's impulse bit. This study confirmed the successful operation of the testing platform under vacuum conditions.

1. Introduction

Lean satellites are those that seek low-cost and fast mission realization by using non-traditional, risk-taking development and management approaches. As a result of the fast delivery and the low cost, these

satellites are inherently small (Cho et al., 2017). Since lean satellites are rapidly being developed worldwide, along with the rise of mission opportunities and augmentation of capabilities to perform sophisticated tasks, the development process of their attitude control systems (ACS) must react to this trend.

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The validation and verification process of an ACS for lean satellites must be carried out through the use of ground-based research facilities in control and space dynamics. Air-bearing-based testbed platforms have been used since the beginning of the space race between the USA and Russia (Schwartz, J. L., Mason, A. P., and Hall, C. D., 2003). The size and weight of small satellites allow for the setup of an entire satellite model on top of the air-bearing testbed and conduction of the hardware-in-the-loop test in a flight-representative environment.

Air-bearing-based attitude testing platforms are envisioned for the validation and verification of an ACS for lean satellites. Those testing platforms can be developed by using available commercial off-the-shelf sensors and actuators. The fact that they feature high sensitivity to small external disturbances has been taken advantage of for the verification of the most common attitude sensors of an ACS (gyroscope, sun sensor, earth sensor, magnetometer, accelerometer, and inertial measurement unit) and most of the available attitude actuators (cold gas thrusters, magnetic torque coils, and RWs); however, efforts to verify electric propulsion systems (EPS) has not been common.

Due to the current demand for complex missions to be carried out by lean satellites that involve orbit correction maneuvers or deorbiting capabilities, the use of EPS as ACS actuators has become essential. Another example is the case of interplanetary missions, where the natural magnetic field is too weak to use magnet torque coils as the secondary ACS actuator along the spacecraft's interplanetary flight path. Without a secondary actuator, the accumulated momentum in RWs (the primary actuator) cannot be unloaded. To overcome this problem, the use of propulsive devices as secondary actuators would be convenient. Due to their high specific impulse and fewer regulations of hazardous materials, EPS are very promising for that purpose. The main constraint in the verification of such systems using an air-bearing table is the requirement of a vacuum environment for the operation of EPS (Tummala, A. R. and Dutta A., 2017).

This paper presents the implementation of an air bearing in a vacuum chamber, with an air flow high

enough to lift the table but low enough not to jeopardize the vacuum. The operation of an air bearing, which simultaneously requires air and a sustained vacuum environment, seems to be a contradictory objective. There are many obvious problems with their combined operation, but that does not mean that it is impossible. In fact, the application of lithography and high-density optical discs by electron and ion beams has been successful for implementing high-precision linear and rotary air bearing stages into a vacuum environment (Gyungho, K. and Hong, P., 2014), using multistage exhaust and differential pump systems to contain and expel the airflow outside the chamber to maintain the vacuum environment. The problem with these solutions is that they require large chambers with many support structures, which is not compatible with the spherical air-bearing system required for air-bearing-based satellite attitude dynamic simulators. The presented work involved operating spherical air bearing inside a vacuum chamber without any support system to contain the air flow. The technique implemented to maintain the vacuum environment is the regulation of the amount of air flow to a level low enough for the testing of electric propulsion systems within 0.01 Pa (manometric pressure) (Biaggio, L. et al., 2003).

This paper is organized as follows: Section 2 describes the air-bearing testing platform and a VAT used in the experiment. Section 3 describes the operation of the testing platform by a RW and by VAT, as well as the derivation of the thrust impulse bit of the VAT from the measurement of the rotational speed. We conclude the paper with suggestions for future work in Section 4. The results obtained in this research will help to expand the lean satellite mission possibilities when electric propulsion is required.

2. Experimental Set-up

2.1. Air-bearing Operation Inside the Vacuum Chamber

The air-bearing operation inside the vacuum chamber is shown in Figure 1. The airflow is supplied to the air bearing through an inlet fitting into the vacuum chamber, provided by an air compressor at 0.6 MPa (manometric pressure). Before the air enters the

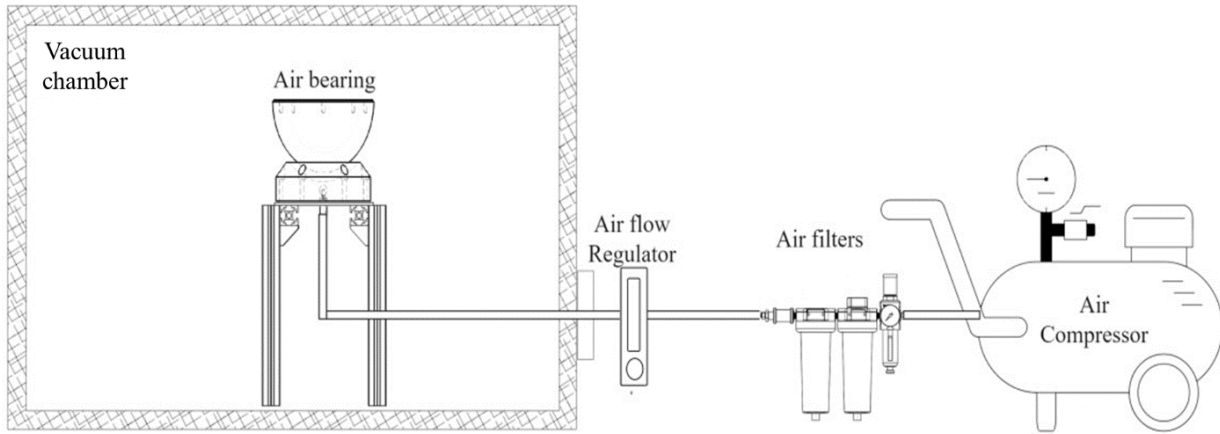


Figure 1. Operation of the air bearing inside the vacuum chamber.

vacuum chamber, it is filtered to eliminate moisture and impurities, then it is controlled using an airflow regulator to the minimum amount sufficient to lift the bearing, but low enough not to jeopardize the vacuum.

The equipment used to operate the air bearing inside the vacuum chamber is as follows:

- **Air bearing:** PIglide Hemisphere A-65 air bearing from Physik Instruments, featuring a hemisphere diameter of 125 mm. The lifting capability of the air bearing in atmosphere is up to 68 kg with 0.55 MPa air pressure. The sphere is mounted on the mating mount with a total contact area of 94.25 cm^2 .
- **Airflow regulator:** MV-302 Mass view from Bronkhorst Company with a control range of 40 to 2000 sccm with a precision of 2% from the reading.
- **Filters stage.** PIglide air preparation kit A-801 from Physik Instruments.
- **Vacuum chamber:** $1150 \times 1000 \times 750$ -mm Stainless steel box, with two-pump system: rotary and cryogenic pump (main). The cryogenic pump used is a ULVAC-16 with a compressor unit C30VR. The cryogenic pump speed is 5000 l/s (Nitrogen) at 20°C .

When the air-bearing semi-sphere is placed inside the vacuum chamber, the force applied to the hemisphere is gravity in a downward direction and air pressure in an upward direction. The total air pressure p is the sum of static and dynamic pressure, and the upward force f_u is given by the product pA , where

$A=94.25 \text{ cm}^2$ is the cross-sectional area of the contact surface between the semi-sphere and the mount. When p is 0.01 MPa, the total f_u is 94.25 N, enough to lift the 4.385-kg testing platform.

Once the air bearing is installed inside the chamber, the operation starts with running the rotary pump, and the airflow into the chamber is gradually reduced. When the pressure reaches the minimum required value to operate the cryogenic pump (10 Pa), we turn on the cryogenic pump and reduce the airflow to the minimum value that keeps the air bearing elevated in the surrounding vacuum condition.

The lifting condition of the air bearing is checked by using an RW on the plane surface of the hemisphere. Through angular momentum exchange, the air bearing starts spinning. When there is not enough airflow to lift the air bearing, even if the RW rotates, the air bearing does not spin.

The pressure inside the vacuum chamber before and after the operation of the air bearing is presented in Table 1. The pressure inside the vacuum chamber reaches $1.0 \times 10^{-3} \text{ Pa}$ after operation of the cryogenic pump and before operation of the air bearing. During operation, the air bearing inside the vacuum chamber reaches $2.4 \times 10^{-2} \text{ Pa}$ by setting up the minimum required airflow to lift the air bearing and keep the highest level of vacuum. In this way, it is possible to lift up to 9.61 kg when the total air pressure p is 0.01 MPa (f_u 94.25 N) and the gravitational acceleration at sea level is 9.8 m/s^2 , keeping a pressure of $2.4 \times 10^{-2} \text{ Pa}$ in the vacuum chamber while operating the cryogenic pump.

Table 1. Airflow and Vacuum Level Inside the Vacuum Chamber

Pump in operation	Airflow into the chamber (SCCM)	Pressure (Pa)
Before air-bearing operation		
Rotary pump	None	5
Cryogenic pump	None	1.0×10^{-3}
After air-bearing operation		
Cryogenic pump	40	2.4×10^{-2}

2.2. Attitude Testing Platform Overview

Once the air bearing is operating inside the vacuum chamber, it is possible to use it as an attitude testing platform. The platform contains sensors, actuator, a bidirectional radio link, an onboard microcontroller, and a power supply system. The table consists of a 6-mm-thick acrylic plate of 450×450 mm, with patterns of threaded and through holes to attach components using bolts or screws. The table is attached to the flat face of the hemisphere part of the air bearing. The overview of the attitude testing platform is shown in Figure 2, and the main components are described in the following subsections.

2.2.1. Attitude Board

The attitude board consists of an Arduino Nano microprocessor platform, an XBee radio transceiver, a three-axis accelerometer (ADXL345), and gyro sensor (MPU-3300). The Arduino Nano is programmed with a LabVIEW Interface for Arduino (LIFA), a toolkit

which allows the configuration of the Arduino microcontroller from the LabVIEW graphical programming environment. The microcontroller is connected with a computer via wireless communication with our LabVIEW interface, using XBee radio modules. Through this data acquisition scheme, the sensor data is acquired, processed, and logged. Additionally, the RW speed and spin direction can be controlled from our LabVIEW interface.

2.2.2. Reaction Wheel

The RW, developed in-house, is used to perform maneuvers in the yaw axis. Our RW consists of a three-phase induction motor (MT 1306) with a rotational speed between 2,500 and 12,000 rpm, and a stainless-steel wheel mass. The speed of the motor is controlled with an Electronic Speed Controller (ESC) Air 15A through a pulse width modulation signal (PWM) from the microcontroller and the spin direction is controlled with a single coil two-pole relay. The connection diagram of the attitude board and the RW is shown in Figure 3.

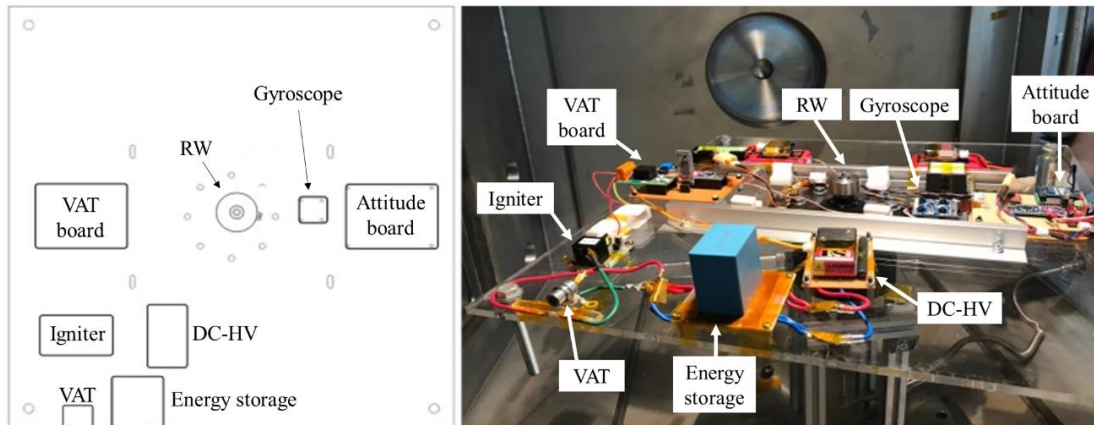


Figure 2. Attitude testing platform.

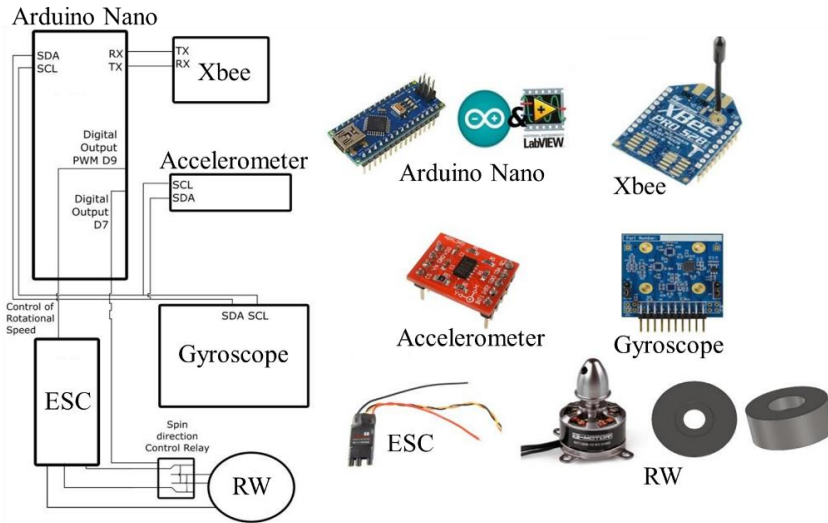


Figure 3. Attitude board and reaction wheel.

The speed of the motor was characterized by a slow-motion camera (with a recording speed of 1200 frames per second) to detect the RPMs of the RW while sending a PWM signal with different values of pulse width to the motor's ESC (Figure 4). The direction of the RW is controlled by triggering the relay placed between the two phases.

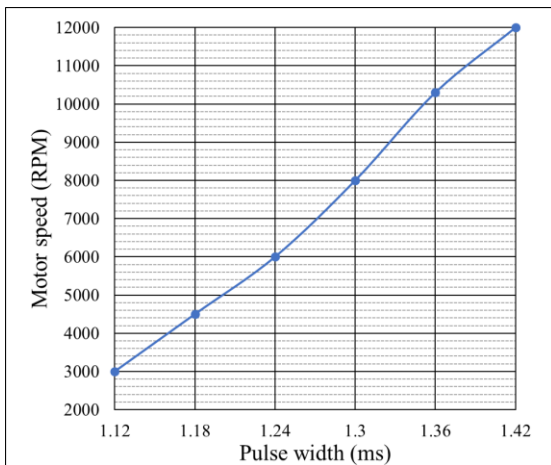


Figure 4. Measured speed of the motor by varying the pulse width of the PWM signal.

Through RW actuation, we performed attitude maneuvers about the yaw axis of the platform in counter- and clockwise directions, with a range of speed from 0.5 deg/s to 16.5 deg/s. Figure 5 shows the results of experimental tests to evaluate the response of the platform's angular rate to different RW speed commands.

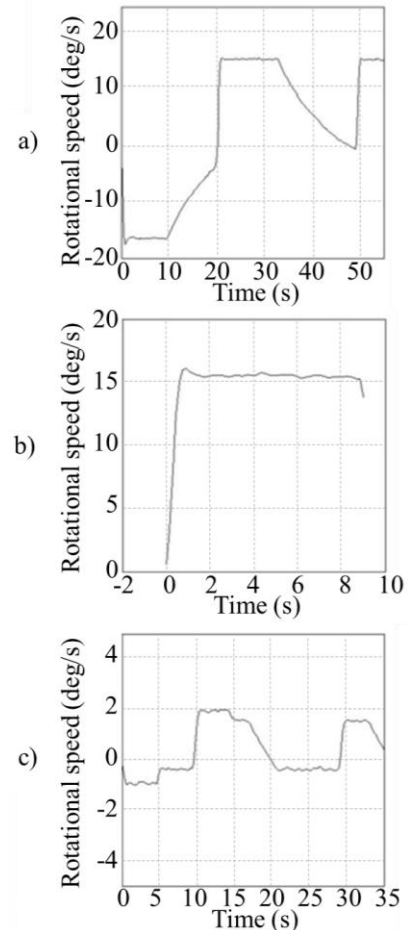


Figure 5. Response of the platform's angular rate when: a) RW accelerates to its maximum RPM in CW and CCW and deaccelerates to zero RPM; b) RW is set to its maximum RPM; and c) RW is programmed to spin in different RPM values.

2.2.3. Vacuum Arc Thruster

The VAT board, the igniter, the Direct Current High Voltage (DC-HV) converter, and the energy storage capacitor (14 μ F) are all supported devices to control and trigger ignitions on the VAT. The VAT consists of three main parts: an anode, a cathode, and an insulator.

- *Anode*: The anode is part of the VAT body made of Aluminum (AL 7075). It is connected to the positive side of the energy storage capacitor.
- *Cathode*: The cathode is made of Carbon Fiber Reinforced Plastic (CFRP). It is often used as a back-face material for solar paddles and has shown discharges with a discharge threshold less than 100 V in plasma-inverted gradient (K. Aheieva, 2016). The cathode is connected to -800 V from the energy storage capacitor.

- *The insulator*: To isolate the cathode and anode a thin layer of non-conductive material was added. The material used was boron nitride, which is resistant to high temperature and thermal shock, and is also used in space radiation shielding applications.

The VAT and the diagram of the support devices are shown in Figure 6.

The operation of the VAT is controlled by its control board. The control board receives commands to turn the DC-HV and the igniter on or off. To operate the VAT, the DC-HV is turned on at the beginning and remaining on during the whole test. When the DC-HV is on, it converts the 5-V input into an 800-V output to charge the energy storage capacitor enabling the VAT operation with an expected impulse bit of approximately 20 μ Ns (K. Aheieva, 2016). The igniter is operated with a tunable frequency to generate sparks at 14.5 kV to trigger discharges on the VAT.

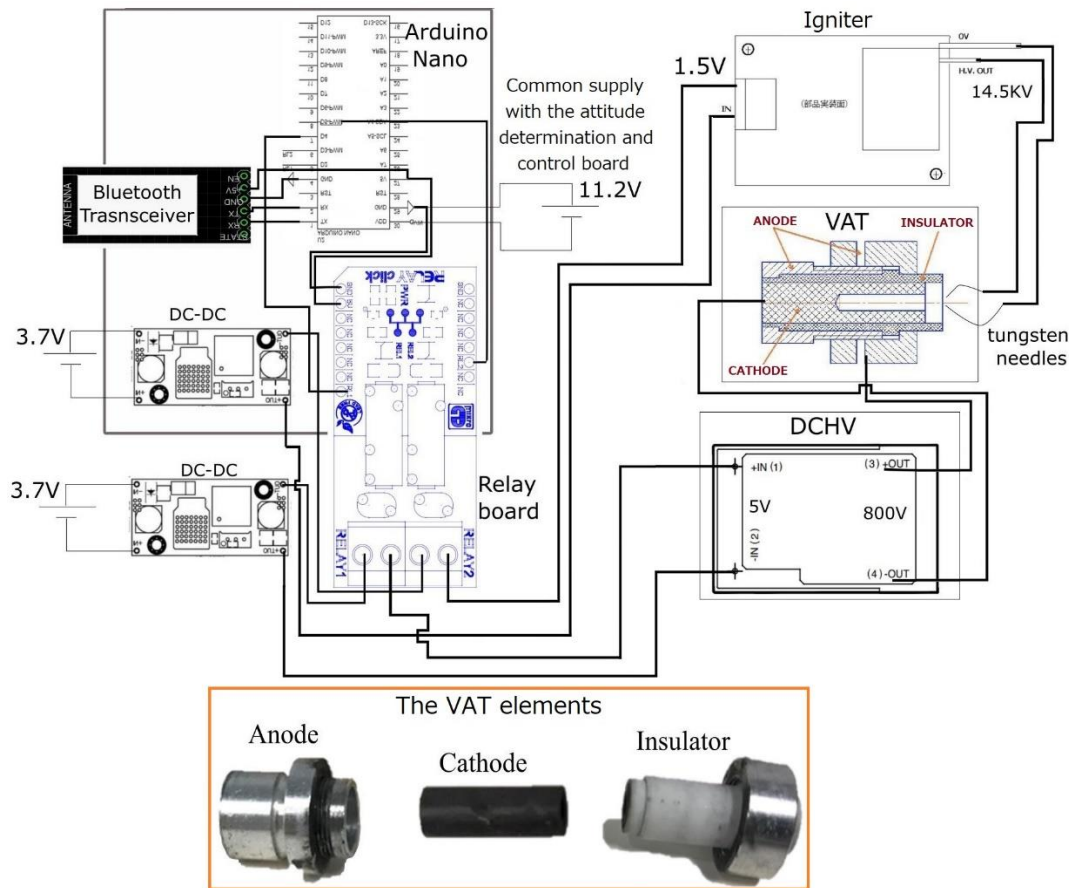


Figure 6. The vacuum arc thruster.

2.3. Testing Platform Balancing and Determination of its Moment of Inertia

Before evaluating the performance of the VAT on the attitude testing platform in a vacuum environment, it is necessary to balance the platform, which is the process of moving the center of mass towards the geometric centroid of the air bearing. This is manually performed by using four M10 bolts symmetrically placed in the corners of the platform as shown in Figure 7. It is possible to add nuts. The center of mass in the yaw axis is adjusted by moving the nuts up and down through the bolts onto each bolt. The balance in pitch and roll axis is adjusted by choosing on which of the four bolts to place the nuts. The table is considered balanced when it looks aligned with the base of the air bearing, with no swinging when the platform is lifted in the air.

To analyze the performance of the actuators on the testbed, the moment of inertia of the platform must be estimated. By using the bifilar pendulum oscillation measurement (Jardin, R. and Mueller R., 2009), it is possible to estimate the moment of inertia by suspending the air bearing with two thin parallel wires (indicated by red arrows in Figure 8), inducing an initial perturbation, and then measuring the oscillation period.

The inertia is calculated by using the following equation:

$$I = mgD^2/4h\omega_n^2 \quad (1)$$

where $D = 400$ mm is the distance between the fastening points on the table; $h = 390$ mm is the length of the wires; and $m = 4.385$ kg is the mass of the system. The period of oscillations is $T = 2\pi/\omega_n = 0.75$ s. The calculated inertia value is 0.062863 kgm².

3. Experiment Results

The VAT was operated on the testbed as shown in Figure 9, where its continuous operation induces a rotational motion on the testing platform. During this test, the RW was turned off and the gyroscope was used to measure the angular rate of the platform. Figure 10 shows the test results of the VAT operation. During the first phase of the test (9-min duration), the VAT was turned off while the testing platform remained static. Subsequently, the VAT was operated in the second phase of the test (35-min duration, starting from an angular rate of -0.4 deg/s), producing 155 discharges. When the VAT was turned off, the air bearing kept spinning at a constant angular rate (0.55 deg/s, $\Delta\omega = 0.59$ deg/s), demonstrating that momentum was induced on the testing platform by the operation of the VAT.

From the results obtained in this test procedure, it is possible to calculate the impulse bit of the VAT. First, we consider the angular momentum equation:

$$L = I\omega \quad (2)$$

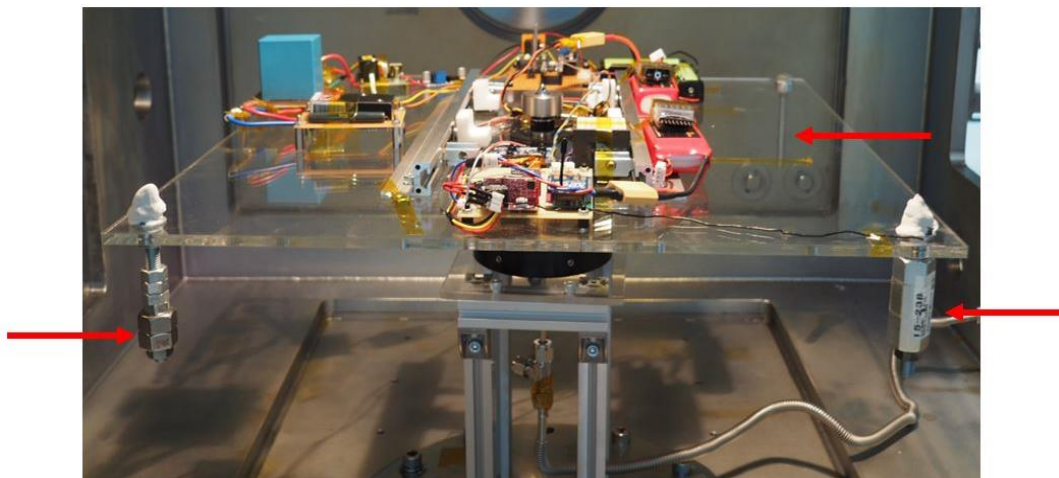


Figure 7. Balance points. The red arrows indicate the location of the balancing masses.

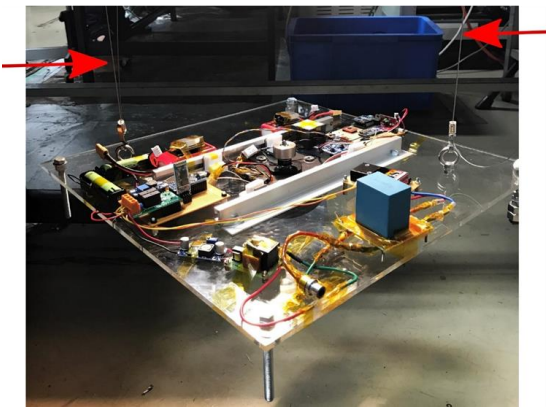
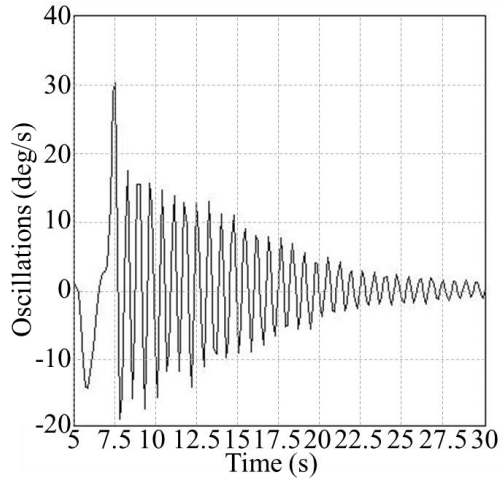


Figure 8. Determination of the moment of inertia by the bifilar pendulum oscillation measurement. The wires that hold the platform are indicated in red arrows.

If we consider an increase in angular momentum (i.e., an increase in the angular rate with a constant moment of inertia) due to a n VAT ignition, Eqn. 2 yields

$$n\Delta L = I\Delta\omega. \quad (3)$$

Expressing Eqn. 3 in terms of the force, we can introduce the term related with the increase in time, ΔT , and the distance of the VAT from the center of rotation r :

$$nFr\Delta T = I\Delta\omega \quad (4)$$

The force multiplied by the change in time is considered the Impulse bit:

$$F\Delta T = I_{bit} \quad (5)$$

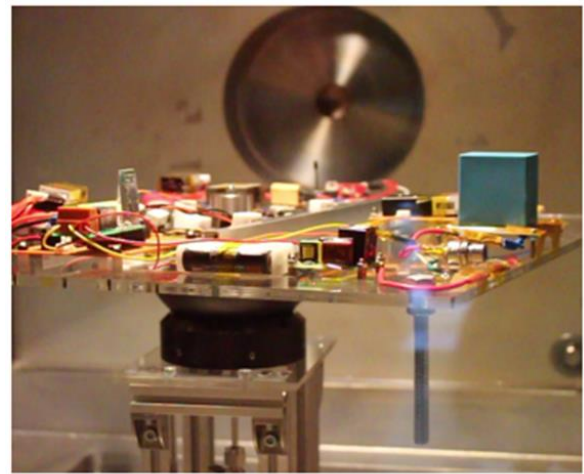
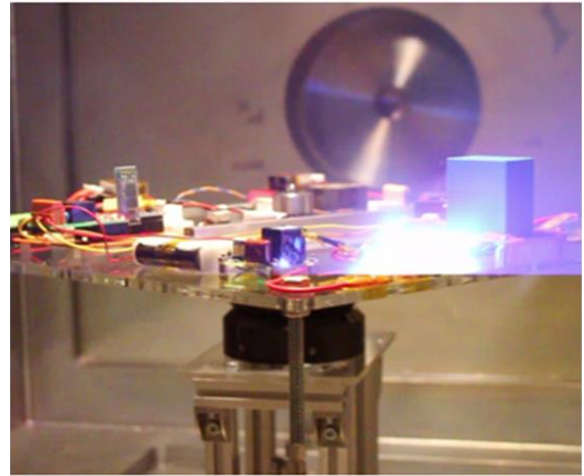


Figure 9. VAT operation.

The impulse bit is calculated using the inertia of the testbed, $I = 0.062863 \text{ kgm}^2$; the increase in the angular velocity, $\Delta\omega = 0.59 \text{ deg/s}$; the required discharges to accomplish the presented performance, $n =$

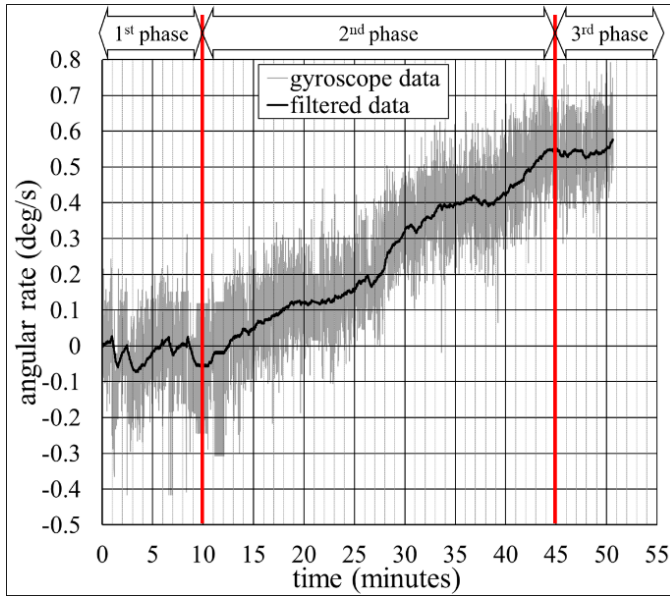


Figure 10. VAT operation results. The period when the VAT was operating is between the two red-line markers (2nd phase).

155; and the distance from the center of rotation to the VAT, $r = 170$ mm:

$$I_{bit} = \frac{I\Delta\omega}{nr} \quad (6)$$

The final result is the impulse bit produced by the vacuum arc thruster on the lean satellite attitude testing platform in a vacuum environment:

$$I_{bit} = 24.6 \mu Ns \quad (7)$$

At this moment, the ignition of a VAT is very unpredictable. Although we sent a command to ignite the VAT once every three seconds, the ignition was successful only 155 times in 35 min, only 22% successful.

4. Conclusion

A lean satellite attitude testing platform based on hemispherical air bearing was successfully implemented in a vacuum environment with the capacity to measure its rotational speed and perform maneuvers in the yaw axis. Its operation is performed by controlling the airflow and taking advantage of the operational vacuum environment, instead of the implementation of

large-scale exhaust mechanisms, demonstrating an effective use of air bearing in a vacuum chamber for the test of the ACS of lean satellites using an electric propulsion system as secondary actuator. The air bearing table was lifted by dry air with 40-sccm flow rate in the background pressure of 2.4×10^{-2} Pa.

As a study case, we demonstrated the performance of a VAT as the ACS secondary actuator to quantify the increase of the angular momentum of the testing platform by its continuous operation. Our results show that the increase of the angular rate of the testing platform $\Delta\omega$, was 0.59 deg/s with 155 ignitions from the VAT. Taking the estimated moment of inertia of the testing platform, we characterized the VAT I_{bit} , resulting in 24.6 μNs , which is very close to the expected value of I_{bit} (20 μNs).

Although we initially planned to demonstrate the momentum dumping of the RW, the total angular momentum that could be generated by the VAT was too small for that purpose. Improving VAT ignition performance or using other thruster systems capable of generating more angular momentum is the next phase of our test campaign. As part of the research activities in Kyutech, the improvement of our VAT and its use as actuator of attitude control systems for small satellites is being investigated. In parallel, we are conducting research activities related with the development and testing of attitude control systems based on electric propulsion systems, for the desaturation of RWs and the execution of orbit correction maneuvers.

The use of air-bearing-based attitude test platforms in an operational vacuum environment contributes to the enhancement of the testing capacities of ACS for lean satellites featuring an electric propulsion system as secondary actuators. Our research contributes to the enhancement of attitude testing facilities, targeting the increase of reliability of advanced ACS for future lean satellite missions that require the use of an electric propulsion system to accomplish their mission objectives.

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