A COMPACT THRUST STAND FOR PULSED PLASMA THRUSTERS

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Abstract

A compact thrust stand has been developed for performance measurements on pulsed plasma thrusters in the 1-100 joule energy range, and used to determine the single-pulse impulse bit and efficiency of a coaxial PPT. The thrust stand, which can support a thruster mass of up to 50 kg on a 20x39 cm platform, is based on a long-period pendulum design which uses the Watt straight-line mechanism, and achieves periods of over 20 seconds by adjusting the center of gravity. A period of 10 seconds is typical for thrust measurements. Platform motion is detected by a linear variable differential transformer, and both DC and impact calibration are employed to achieve an accuracy of ±5% at 150 µN. Single-pulse measurements show the impulse bit of a coaxial Teflon PPT to be linear with energy at 60 µN-s/J, at an efficiency of 12 - 17% at 600 seconds specific impulse.

Introduction

Interest in satellites of mass less than 100 kg has resulted in a propulsion requirement for microthrusters, particularly the Pulsed Plasma Thruster (PPT). The design of a small satellite affects the propulsion system by limiting its power, mass, and fuel system complexity. Options for the on-board propulsion systems of small satellites include both advanced chemical and electric propulsion devices. However, the PPT is unique in that it offers operation at low power in simple, solid-state devices that are highly reliable, compact, and lightweight with a high specific impulse and a high power processing capability. These benefits make the PPT useful for orbit raising and acquisition of small satellites. PPTs also offer a small, discrete impulse bit which gives satellites mission advantages such as accurate positioning, attitude control, drag makeup, and constellation stationkeeping.

Critical to the success of all PPT programs is the ability to take accurate, direct thrust measurements with high resolution and sensitivity. An early sensitive PPT thrust stand was the Micropound Extended Range Thrust Stand (MERTS), developed by the Goddard Space Flight Center in the early 1970s. This torsional device could measure both individual pulses and average repetitive-thrust levels as low as 25 µN. Thrust measurements of the PPT on the LES-6 spacecraft in 1973 at the MIT Lincoln Laboratory were performed by attaching the PPT to a simple pendulum, with the thruster fired synchronously with the motion of the pendulum, resulting in a build up of oscillatory motion. In the mid 1970s a torsional “swinging gate” thrust stand was developed by Fairchild Republic Co. for the sole purpose of testing PPTs, measuring both individual pulses and average repetitive-thrust levels as low as 200 µN. The Fairchild thrust stand was reconstituted at Princeton University for measurements on magnetoplasmadynamic thrusters and is still in use for PPTs today.

In 1994, following a renewed interest in PPTs, a PPT Thrust Stand was developed at the NASA Lewis Research Center. This device is also a torsional thrust stand with the capability of individual-pulse and average repetitive-thrust measurements and uses flexural pivots to provide a required low torsional spring constant without friction. A duplicate of
the NASA stand is currently in operation at the Air Force Research Lab (AFRL), Edwards AFB. The size and complexity of the Lewis stand design limit its use to larger vacuum facilities.

This report discusses the details of a new thrust stand for microthrusters that is both compact and lightweight. The resolution of the thrust stand is demonstrated with performance measurements of a newly developed PPT that has a coaxial electrode geometry. Impulse bit measurements for individual pulses are given and are compared to time-averaged thrust values obtained during repetitive operation.

**UIUC Compact Thrust Stand**

The thrust from PPTs ranges from 10 pN to 1000 pN, a level that makes accurate resolution difficult. In addition, instrumentation noise can have a major influence on accuracy, and pulsed operation imparts transient forces to the thrust stand, introducing a need for mechanical filtering. Some of these problems are overcome when the thrust stand has a natural frequency much lower than the firing frequency of the thruster, thrust stands built for microthrusters are based on pendulum systems. Even a small impulse bit is large enough to overcome the natural damping of a long-period thrust stand system at low amplitudes.

Because available thrust stands are intended for large tank facilities, the UIUC thrust stand was designed to be compact and lightweight, consistent with the 36-inch diameter of the UIUC vacuum facility and, ultimately, with a 24-inch bell jar. The design specification is for a footprint of 55 cm (22 inches), a height of 40 cm (16 inches), a 50 kg mass capability, a period of >10 seconds, and no counterbalance requirement. Where possible, successful design elements used in previous PPT thrust stands were incorporated, with the strongest contribution being the NASA Lewis stand. A thrust level of 50 pN with no more than 5% uncertainty for repetitive-pulse operation and calibration was sought.

**Thrust Stand Concept and Theory**

The concept for the new design, shown in Fig. 1, was suggested by Burton, who in 1967 performed experiments based on a *Scientific American* article on long-period pendulums. The device, developed by N. Lindenblad, implements straight-line motion initially developed as a mechanism for steam engines by James Watt in 1784. The linkage consists of a horizontal bar supported at one end by a hinged lever and is suspended at the other end by a flat ribbon of spring steel. The ribbon in turn is hinged in the middle by a short length of spring stock turned at right angles to give the entire suspension lateral freedom. With the lever and ribbon given equal length, the center of the horizontal bar moves in a straight line when pushed through its axis. A sliding
bob is used to adjust the center of gravity (c.g.) and is located on the horizontal bar. The level of the system is controlled by adjustment screws located on the base. Ignoring friction and any torsional restoring torque in the pivots, if the c.g. is located at the geometrical midpoint (position 'A', Fig. 1) an infinite period will result. Sliding the c.g. slightly forward (position 'C') results in an unstable position. Sliding the c.g. slightly backwards (position 'B') results in a long period. By fine control of the c.g. location on the horizontal bar, the desired period can be obtained.

The schematic of "Watt's Pendulum," shown in Fig. 1, can be used to analyze the thrust stand performance. The center of mass is represented by the shaded circle, which is located a distance $x_{cm}$ from the back platform pivot.

For small displacements, the angle $\theta$ is approximately the same on both pendulum linkages of length $R$. The distance $L$ between the pivots has a center point represented by $c_p$, which for small $\theta$ moves horizontally a distance $d$ with no vertical displacement $h$. Analysis of the geometry defines an equivalent simple pendulum of length $R_s$ with deflection angle $\theta_s$. Assuming that the pivots are frictionless with a torsional spring rate, the period, $\tau$, of this system is:

$$\tau = 2\pi \sqrt{\frac{R_s}{g + \frac{k_s}{mR_s}}}$$

where 

$$R_s = \frac{R}{2\left(\frac{L}{2} - x_{cm}\right)} \left(\frac{L}{\cos \alpha}\right)$$

g is gravity, $\alpha$ is the pitch angle of the stand from horizontal, and $k_s$ is the total torsional spring rate of the pivots. As the equation shows, the period is not sensitive to $m$, $\alpha$, or $k_s$ because $k_s << mR_s$ and $\cos(\alpha) = 1$ for small $\alpha$.

Figure 2 plots the period versus the center of mass location for this thrust stand ($k_s = 73.5$ N-cm/rad, $L = 362$ mm, $R = 136.5$ mm). The period gets large as $x_{cm}$ approaches $c_p$.

Details of Design

The thrust stand with the coaxial PPT is shown in Fig. 3. The platform area measures 39 cm L x 20 cm W and weighs approximately 5 kg without thruster. The overall frame dimensions are 46 cm L x 30 cm W x 37 cm H. The total weight is about 15 kg. The total allowable platform mass, limited by the flexural pivots, is 50 kg. Inside the test chamber, the thrust stand rests on a vibrationally isolated platform to minimize vibration resulting from the facility and the vacuum pumps.
The thrust stand can be divided into eight systems:

1. Frame  
2. Platform  
3. Counterweight  
4. Balance Control
5. Steady Calibration  
6. Impact Calibration  
7. LVDT  
8. Data Acquisition

Rectangular aluminum tubing is used to provide structural stiffness to the frame and platform. For stability, the platform is supported in front with two inverted pendulum arms. The platform is suspended in the back with one pendulum arm, which has a flat ribbon of stainless steel foil in its middle for lateral flexibility. A total of eight Lucas flexural pivots¹³ are used, each with torsional spring rates of 9.2 N-cm/rad, the lowest available with the required load capacity.

Balance is controlled with fine adjustment screws located on the frame's bottom plate. “Roll” balance is accomplished by adjusting two screws manually during thrust stand setup. “Pitch” balance is similarly provided by a remotely-operated step motor. Since pitch affects the location of the null-point, this adjustment allows accurate horizontal positioning of platform.

An adjustable center of mass position is used to control the period, with at least 10 seconds desired for testing. A period of over 20 seconds has been achieved. Examination of Eq. (1) or Fig. 2 indicates that the center of mass must be ~1 mm from the center point.

Since the vacuum facility shifts slightly during vacuum pump-down, drift can occur. The center of gravity position is controlled remotely with a step motor located underneath the platform. Here, a 250 - 750 g counterweight mounted on a lead screw can be adjusted horizontally in increments of 55 μm. This results in a center-of-mass movement of only 1 - 3 μm. Horizontal platform motion is detected to within ±1 μm by a Schaevitz DTR-451 linear variable differential transformer (LVDT).

It was initially thought that damping of the platform's oscillations would be needed. Hence, an oil-filled fluidic damper was implemented. However, after setting up the thruster and thrust stand for testing it was found that the electrical wiring for systems on the platform and thruster provided ample damping, and the oil system was removed.

Steady calibration for repetitive-pulsing PPT operation is obtained with the use of two 250 μN weights suspended on a 12 μm diameter Spectra™ fiber fed over a custom-built pulley to pull on the platform. This frictionless calibration pulley has a torsional restoring torque which limits the effects of pulley hysterisis during calibration. The thin fiber was needed to eliminate the effects of stiffness on calibration. The free end of the fiber is attached to a Teflon pulley mounted on a step motor, which is attached to the upper structure of the frame. Remote control of the motor raises or lowers the fiber to place the weights in tension underneath the calibration pulley, as has been done elsewhere.⁷ By adding and removing the weights incrementally, a stair-step pattern results on the LVDT output for steady-state calibration.

Impact calibration for single-pulse PPT operation is obtained with a force transducer attached beneath the platform. An impact hammer, activated by a remotely-controlled solenoid, impacts the force transducer. The time-integrated output voltage and calibration constant of the force transducer are then used to obtain the impulse bit. By examining the LVDT output, the recoil velocity of the platform is obtained by subtracting any platform velocity prior to impact from the velocity immediately following impact. The effective platform mass is then calculated from \( I = mv \), and is used as a calibration value for single-shot measurements.

A computer-based data acquisition system is used to obtain high accuracy and resolution. For all tests and calibrations, LVDT output is retrieved on a 486 PC with a 12-bit data acquisition card. Data is continuously sampled at 50 Hz, and moving-average values are recorded and plotted at 2 Hz. For single-pulse tests and impact calibrations, the raw LVDT output is obtained at 660 Hz on a 286 PC with an 8-bit, 10 MHz digital oscilloscope. Output of the force transducer is recorded by a digital oscilloscope at 500 kHz and downloaded to a second 486 PC where the plot is integrated. The combined use of these systems allows for precise numerical analysis.
Repetitive Pulse Operation

Measuring the time-averaged thrust of a PPT on the thrust stand is only possible because the thruster repetitive-firing rate is much greater than the natural frequency of the thrust stand. The thrust is then balanced by the thrust stand restoring force, which increases linearly with distance from the thrust stand neutral position. The force measurements are quantified by comparing the deflection created by the thruster to those created by calibration weights. In these experiments the firing rate is ~1 per second, and the thrust stand period is 10 seconds.

Initially, the thruster is positioned with the thrust axis horizontal, and the platform is stabilized with a period of at least 5 seconds. A mechanical level is used to assist in properly balancing the system. The chamber is closed and evacuated for ~3 hours as drift decreases. The remote-controlled pitch is then used to center the LVDT core inside its coil, and the remote-controlled counterweight is adjusted to achieve a period of at least 10 seconds. Calibration is typically performed before and after a thrust test. This calibration method is depicted in Fig. 4, which shows a single 302 μN weight used before and after a PPT firing for average thrust calibration. Additional weights can be applied to obtain a more accurate calibration.

Figure 4 shows thrust stand drift occurring over 500 seconds, which is attributed to mechanical stresses on the vacuum chamber, thermal effects, and the thruster and thrust stand cabling. The corrected waveform assumes a constant drift rate. Under the longer time frames needed for cycling additional calibration weights, the drift can oscillate, which introduces further uncertainty into the calibration. Therefore only one weight is currently cycled, and the total time required for calibration and firing is kept to a minimum.

Thrust can be determined in two ways. The LVDT output can be printed out, and a base-line with a slope equal to the drift rate is “eyeballed” through the zero-thrust data. Using this method on the data presented in Fig. 4 predicts a thrust of 279 ± 17 μN (6% uncertainty).

A second method is to analyze the data with data-reduction software, as shown in Fig. 4. The software can be used to correct the data for drift and then to numerically determine the base-line, calibration-line, and thrust-line from the root mean square of the data. Applying this method to the data in Fig. 4 predicts a thrust of 282 ± 8 μN (3% uncertainty).

![Fig. 4 Raw and drift-corrected data (assuming constant drift) for calibrated, repetitively-pulsed PPT test. Calibration weight is 302 μN.](image)

Single Pulse Operation

The long period of the UIUC thrust stand is advantageous for single-pulse measurements as it provides, upon firing, a damped sinusoid progressing for well over 100 seconds, or more than 10 cycles, as depicted in Fig. 5. Calibration, as discussed earlier, is accomplished via a hammer impacting on a force transducer. The force of the hammer blow is remotely controlled by a potentiometer which limits the current on the solenoid.

Data reduction uses the raw output from the LVDT, displaying the motion of the thrust stand. The mean slope of the curve before and after time zero gives the change in stand velocity at impact. Using either a straight line drawn through the data or a linear numerical fit of the region, the velocity is calculated.
The force transducer output provides \( I_{\text{bit}} = \int F \, dt \). Therefore the effective mass of the platform is calculated from \( m = I_{\text{bit}} / \Delta v \).

Alternatively, a damped sinusoid curve fit can be performed on the 2 Hz moving-average LVDT signal. From the equation for an underdamped simple pendulum of length \( L \) and amplitude \( A \), since \( I_{\text{bit}} = \frac{m \cdot v}{F} = \int F \, dt \), we can derive:

\[
x(t) = \frac{\int F \, dt}{m \cdot \omega} \exp(-\beta t) \sin(\omega t)
\]

Differentiating Eq. (2) yields \( v(0) = \int F \, dt / m = L \cdot A \cdot \omega \).

Fitting this to the data with a known \( \int F \, dt \) yields both the period and the effective mass, from which the \( I_{\text{bit}} \) of the thruster can be calculated from \( I_{\text{bit}} = m \cdot \Delta v(0) \).

Use of this technique requires that the thrust stand be motionless prior to the pulse.

### Verification of Thrust Stand Measurements

Verification of the thrust stand was accomplished by testing an early version of the PPT in repetitive mode on both the UIUC thrust stand and the torsional thrust stand located at AFRL. Table I compares the data. The difference in measured thrust is a result of different pulse rates used at the two facilities, as demonstrated by the excellent agreement in the computed impulse bits, where \( I_{\text{bit}} = \text{thrust} / \text{frequency} \).

### Thrust Stand Resolution

With the current design, the thrust stand has a resolution of about 8 \( \mu \)N in repetitive-pulse operation. Thus, 160 \( \mu \)N can be measured within 5% uncertainty, and 80 \( \mu \)N can be measured within 10% uncertainty. The resolution can be improved by providing for oscillation damping and by reducing or eliminating drift. Preliminary analysis indicates that these improvements can reduce the resolution to 2 \( \mu \)N, indicating a measurable thrust of 4 \( \mu \)N with 5% uncertainty.

### UIUC Coax PPT Results

The performance of a coaxial PPT, seen in Fig. 3, was measured on the thrust stand at low energies (5 - 7.5 J) in single-pulse operation. The thruster has an expansion nozzle area ratio of 13:1. The electrode
diameters are 43 mm (cathode) and 4.8 mm (anode). The thrust of the coaxial PPT is both electromagnetic and electrothermal, as given by:

\[ I_{bit} = \int T_{em} \, dt + \int T_{et} \, dt = K \int I^2 \, dt + \int \int p \, dA \, dt \quad (3) \]

The electromagnetic contribution is independent of the ejected mass, depending only on the inductance gradient factor:

\[ K = \frac{\mu_0}{4\pi} \left[ \ln \frac{r_{\text{cathode}}}{r_{\text{anode}}} + 0.75 \right] \quad (4) \]

where the term in brackets is \(-3\). The electrothermal contribution is dominated by the pressure force on the anode created by the ohmic heating of the ablated mass. Ideally, the pulse energy is added on a time scale short compared to the acoustic time in the plasma so that the pressure pushes on the anode for a time on the order of \( L/c \) where \( L \) is the plasma axial length and \( c \) is the sound speed.

The Teflon propellant was found to ablate at a rate proportional to discharge energy of 10 \( \mu \)g/J. The thruster was driven by an 8 \( \mu \)Fd capacitive pulse-forming network through a 10 cm-long coaxial cable which provided a non-reversing current pulse of \(-2 \mu s\) full width at half maximum. The non-reversing pulse transfers \(-95\%\) of the stored energy to the discharge.

![Fig. 6 Thrust stand measurement of coax PPT showing impulse bit linear with stored energy at 60 \( \mu \)N-s/J.](image)

The impulse bit is shown in Fig. 6 as a function of energy, and is linear with energy at \(-60 \mu\)N-s/J, approximately three times the level achieved by the LES-8/9 (Fig. 6). The electromagnetic contribution to \( I_{bit} \) at these low energy levels is only a few percent of the total.

Incorporating the ablated-mass measurements, the efficiency can be calculated from:

\[ \eta = \frac{I_{bit}^2}{2A_dE} \quad (5) \]

and is plotted in Fig. 7 versus the discharge energy.

![Fig. 7 Efficiency of coaxial PPT at 5 - 7.5 J in comparison to the LES-8/9.](image)

The measured efficiency reaches 18\% at 7.5 J, approximately double that achieved by the LES-8/9 at 20 J. The \( I_{sp} \) for these measurements was 600 s.

**Summary and Conclusions**

A thrust stand was developed with a period >10 seconds, 50 kg allowable platform mass, 55 cm footprint, and 8 \( \mu \)N resolution. Both repetitive-pulsed thrust measurements and single-pulse impulse bit calculations were performed on a coaxial PPT.

The UIUC coaxial PPT has demonstrated efficiencies which exceed previous rectangular geometries.

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References


