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Thomas W. Haag
Lewis Research Center
Cleveland, Ohio

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Thomas W. Haag
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

A torsional-type thrust stand has been designed and built to test Pulsed Plasma Thrusters (PPTs) in both single shot and repetitive operating modes. Using this stand, momentum per pulse was determined strictly as a function of thrust stand deflection, spring stiffness, and natural frequency. No empirical corrections were required. The accuracy of the method was verified using a swinging impact pendulum. Momentum transfer data between the thrust stand and the pendulum were consistent to within 1 percent. Following initial calibrations, the stand was used to test a Lincoln Experimental Satellite (LES-8/9) thruster. The LES-8/9 system had a mass of approximately 7.5 kg, with a nominal thrust to weight ratio of 1.3×10^{-5} . A total of 34 single shot thruster pulses were individually measured. The average impulse bit per pulse was $266 \mu\text{N-s}$, which was slightly less than the value of $300 \mu\text{N-s}$ published in previous reports on this device. Repetitive pulse measurements were performed similar to ordinary steady-state thrust measurements. The thruster was operated for 30 minutes at a repetition rate of 132 pulses per minute and yielded an average thrust of $573 \mu\text{N}$. Using average thrust, the average impulse bit per pulse was estimated to be $260 \mu\text{N-s}$, which was in agreement with the single shot data. Zero drift during the repetitive pulse test was found to be approximately 1 percent of the measured thrust.

Introduction

Pulsed plasma thrusters (PPTs) are electric propulsion devices in which the propellant is accelerated electromagnetically. Pulse durations are typically on the order of one to ten microseconds. PPTs were studied during the 1960's and tested by the US in an orbital flight experiment launched in 1968.¹ Operational status was reached on board NOVA navigation satellites beginning in 1981.² The NOVA system uses solid fluorinated polymer as an ablatively dispensed propellant and is fired at a repetition rate of up to 1 pulse per second. The unit has an average power input of about 30 watts and achieves specific impulse values approaching 1000 seconds. The small impulse bits of each firing are used for very fine orbital corrections of the NOVA vehicle, and the PPT is currently performing this mission successfully.³

Recent interest in small satellites has sparked renewed interest in PPTs. Available electric power on small satellites may be limited to less than 0.01 kW, which eliminates most steady-state forms of electric propulsion from consideration. PPT power throttling is managed simply by reducing the pulse repetition rate and does not affect performance. The simplified solid propellant distribution arrangement of PPTs eliminates the need for valves, tanks, or precision metering components. Strict temperature controls often required for pressurized fluid propellants are also eliminated. Being a relatively inert solid, fluorinated polymer does not require special handling protection often needed when loading toxic liquid propellants.

A program to develop advanced PPTs for future mission applications has been initiated.⁴ Goals of this program are to increase delivered total impulse by a factor of two while reducing system mass by the same factor as compared to state-of-art devices. New propellant options are also being explored.⁵ Direct thrust measurements will be essential to the success of this program. Impulse bits on the order of $300 \mu\text{N-s}$ are anticipated from thrusters with several kilograms mass. The average thrust-to-weight ratio is significantly below that of steady-state electric propulsion (EP) devices and a specialized thrust balance is required.

The most sensitive PPT impulse measurement capability in the United States was developed by Goddard Space Flight Center during the early 1970s.⁶ Designated as the Micropound Extended Range Thrust Stand (MERTS), this device was used to measure both individual pulses and average repetitive thrust at levels down to $25 \mu\text{N}$. A custom-built differential plate capacitance system was used to measure thrust stand deflections to a resolution of $2.5 \times 10^{-8} \text{ m}$. Both a null balance method and a calibrated displacement method were implemented. A rotary thruster mount was used to vector the plume at different angles in order to determine asymmetric side forces. Oscillation damping was accomplished with an electronic feedback circuit acting through an electromagnetic driver. A wireless system of optical and radio links was used for thruster telemetry and control. The thrust stand also had a built-in, variable-position, counterweight arrangement and required no special adjustments to operate thrusters of very different weight or thrust levels. Calibration was performed by sending current through an electromagnetic forcing coil.

This method was used for pulsed and steady-state calibration.

Testing at the MIT Lincoln Laboratory was performed with a simple pendulum thrust stand.⁷ The thruster was fired in synchronism with the natural frequency of the pendulum, resulting in an observable build up of oscillatory motion. Measuring the changes in amplitude allowed determination of the average value of impulse per shot.

A Pulsed Electrothermal Thruster (PET) was tested by GT-Devices in the mid 1980s.⁸ Liquid water flashed to a vapor and was heated in an arc discharge to propel the PET. Water PETs could be operated in single pulse or repetitive modes. The thrust stand used to test the PET consisted of a linear rail arrangement passing through the vacuum tank, and sealed with a flexible diaphragm. Typical impulse bit measurements were on the order of 5 mN-s. Impulse was determined by observing the instantaneous velocity change of the thrust stand as a result of thruster firing. An inductive proximity probe provided displacement information, which was then differentiated to obtain velocity. The system was calibrated by striking the thrust stand with a solid pendulum. Thrust stand response was compared with the known momentum delivered by the pendulum.

A torsional thrust stand was developed by Fairchild Republic Co. in the mid 1970s for the purpose of testing PPTs.⁹ Both individual pulse and repetitive operation were performed at thrust levels down to 200 μ N. Leveling motors maintained the correct null position and a linear variable differential transformer (LVDT) measured thrust stand deflections. An oil filled fluidic damper was used to dissipate oscillations resulting from the thruster firing. A ball calibrator was developed to provide *in-situ* thrust stand calibrations. Steel ball bearings were conveyed upward and allowed to accelerate down an inclined plane, where they impacted the thrust stand. Data from the calibration was compared directly with that of actual thruster operation to quantify performance.

Following the completion of earlier PPT development programs, both the Goddard and Fairchild thrust stands were eventually discarded. A new thrust stand has recently been built and tested for the purpose of evaluating the Lincoln Experimental Satellite thruster (LES-8/9) and future generation PPTs. This stand employs a torsional design, similar in size to that used by Goddard and Fairchild,^{6,9} and has been used to measure individual thrust pulses as well as average thrust during times of repetitive pulsed operation. Pivot arm movement is damped electromechanically through a feedback loop, which can smooth the thrust signal at pulse rates down to about 1 Hz.

This report discusses the details of the new thrust balance and gives examples of actual PPT performance. The impulse bits of individual thruster pulses are presented, and these measurements are compared to time averaged thrust values obtained during repetitive operation.

Pulsed Plasma Thrusters

PPTs are a type of magnetoplasmadynamic thruster in that they accelerate propellant predominantly through electromagnetic forces. With a PPT this occurs during a brief but powerful pulse, typically at peak powers in the MW range and for durations on the order of microseconds. This pulsed mode allows performance and benefits associated with high power to be attained with low average power systems. While early development of PPTs employed gaseous propellant, a solid fluorinated polymer rod has replaced gas in most applications. Solid propellant is vaporized through ablation, eliminating the need for fast acting gas valves and flow control.

A PPT is prepared for firing by first charging the main storage capacitor. The charge rate can be determined by the spacecraft power limitations without affecting thruster performance. The electrodes can remain directly connected to the capacitor during the charging cycle as long as there is no conductive path from anode to cathode. Even at a full charge of 1000 V the thruster is designed not to fire spontaneously. The discharge is commonly triggered using a semiconductor spark plug. This device emits a small quantity of free electrons when activated, and brings about an avalanche breakdown across the main electrodes. As the capacitor is discharged, polymer from the surface is vaporized and ionized into a current carrying plasma. The plasma is ejected from the thruster via Lorentz forces created by the discharge. Once the discharge is extinguished the main capacitor may be recharged for the next pulse.

The LES-8/9 PPT was designed to operate at a nominal average power of 30 watts, and a pulse repetition rate of about 2 Hz. There are two separate discharge ports on each thruster assembly which are vectored at 60 degrees to each other. Each port has a separate pair of electrodes and propellant track, but both sides share the same storage capacitor and charging system. Each thruster port is controlled independently through signal wires. The thruster was designed to deliver a nominal 300 μ N-s impulse bit from either port. It has a mass of about 7.5 kg, representing an average thrust to weight ratio of about 1.3×10^{-5} .

Principle of Impulse Measurements

Impulse can be defined as the cumulative effect of an applied force over a specific time interval. It can be shown that the impulse needed to propel a body is simply the product of its mass and velocity. According to Newton's third law, the mutual reaction force between the propellant and the thruster occur at the same magnitude and for the same duration of time. The impulse delivered to the propellant is identical, but in opposite direction to that of the thruster. The thruster, of mass m , recoils in response to a discharge such that

$$v = \frac{I}{m} \quad (1)$$

where v is the recoil velocity, and I is the impulse delivered. Unfortunately, the sinusoidal movement typical of most thrust stands makes instantaneous velocity measurements difficult. Velocity must be measured the instant after the thruster fires, which introduces possible noise problems due to electromagnetic interference and structural harmonics. An alternative is to obtain critical signal data after such disturbances subside. Conservation of energy makes this technique possible. The kinetic energy E delivered to the thruster is

$$E = \frac{1}{2}mv^2 \quad (2)$$

If the recoiling thruster collides with an elastic spring such that energy is conserved (*i.e.* frictionless), then all of the kinetic energy will be transformed into strain energy in the spring such that

$$E = \frac{1}{2}mv^2 \Rightarrow \frac{1}{2}kx^2 \quad (3)$$

where k is the spring stiffness, and x is the spring deformation. By rearranging eq(3), the maximum deformation of the spring becomes

$$x = v\sqrt{\frac{m}{k}} \quad (4)$$

Substituting eq(1) into eq(4)

$$x = \frac{I}{\sqrt{mk}} \quad (5)$$

When using a torsional thrust stand, the inertial term m can be difficult to quantify directly due to the radial distribution of various masses. However, all spring-mass systems have a characteristic natural frequency, ω_n , determined by

$$\omega_n = \sqrt{\frac{k}{m}} \quad (6)$$

Substituting for the mass term in eq(5) yields

$$x = \frac{I\omega_n}{k} \quad (7)$$

When used operationally, x is measured as the maximum deflection of the thrust stand after an impulse is applied. k is determined by exerting a known steady force along the thrust axis of the stand and observing the deflection. ω_n is

determined by counting the undamped frequency of oscillation of the thrust stand. Using the above measured quantities, the unknown impulse bit is calculated as

$$I = \frac{xk}{\omega_n} \quad (8)$$

Thrust Stand Design

Momentum impulse measurements are considerably different from conventional steady-state thrust measurements. Pulsed operation imparts highly transient forces to the thrust stand which require special consideration. Also, PPTs typically have very low thrust to weight ratios which make accurate resolution difficult.

Initial attempts at using a modified arcjet thrust stand were met with marginal success. The arcjet stand featured a four bar linkage, inverted pendulum configuration.¹⁰ While this linkage design maintained constant thrust axis alignment with the facility, its added complexity resulted in less precise movement than required and a somewhat jittery response with pulsed thruster applications. Because of this, a new torsional thrust stand design was built specifically for testing the PPT. A simple torsional thrust stand has only one rotational axis, and is inherently more stable than an inverted pendulum arrangement. There is much precedent for using a torsional arrangement with PPTs, such as the MERTS and Fairchild Republic installations.^{3,9} A torsional thrust stand basically consists of a swinging gate structure which is free to rotate about a vertical axis. The thruster is mounted on the end of the gate or arm, at some radial distance from the center of rotation. The thrust axis is aligned to be tangent to the sweeping motion of the arm, such that when the thruster is fired, the arm responds by rotating about its axis. This rotation is opposed by a torsional restoring force which returns the arm to a designated neutral position once the thruster is turned off. With most thrust stand designs, the stiffness of the restoring force is very linear and repeatable. For steady-state operation, measured displacement may be used as a means of comparison between the unknown engine thrust and an established calibration force. Pulsed thrust measurements must be obtained differently since the spring-mass time constant of a thrust stand is often orders of magnitude longer than the duration of the actual pulse. Detailed explanations of these issues are included in the following section.

The thrust stand described herein was built in three separate sections (Fig. 1). A torsional arm supported the PPT and counterweights. The rotational axis of the arm was held vertically by a stationary framework which also served as a reference for displacement measurements. The stationary framework can be leveled in both the x and y direction through the use of remotely operated motors. A

lower frame served as a foundation for the leveling system and, for the measurements described herein, was bolted rigidly to the inside of the vacuum tank. It aligned the leveling screw arrangement with the stationary structure, and enabled the entire thrust stand assembly to be relatively portable.

The torsional arm was constructed from welded 5 cm x 7.5 cm rectangular aluminum tube sections. This resulted in a stiff, light weight structure with a high natural frequency. As mounted, the PPT exhaust ports were positioned at 0.59 m radial distance from the rotational axis and fired tangent to the arm. A stack of stainless steel counterweights were placed on the other end of the torsional arm, opposite the rotational axis from the thruster. These weights were found to be effective at reducing zero drift in thrust measurements. Since the PPT has a thrust to weight ratio on the order of 1.3×10^{-5} the stand was extremely sensitive to horizontal misalignment. Minute distortions of the vacuum facility caused by cooling irregularities in the diffusion pumps initially resulted in excessive thrust signal drift. Counterweights drastically reduced this sensitivity because gravitational variations resolved onto the thruster were canceled by equal, but opposite, forces from the counterweight. About 95 percent of the thruster weight was offset by the counterweight. The remaining 5 percent was retained as a convenient way of manipulating the neutral position with the leveling controls. The rotational axis consisted of two commercially available flexure pivots, each 13 mm in diameter. Both of the pivots were aligned along the vertical axis and clamped in position on the torsion arm and stationary frame. The upper flexure was constrained in the radial direction, but allowed to accommodate axial expansion within the arm. The lower flexure supported the entire axial weight of the arm, but both flexures exerted the torsional restoring force in the thrust stand.

The stationary structure was made from the same type of rectangular tube sections as the torsional arm, and was welded throughout. Two inclinometers are mounted on this structure and used as inputs to keep the thrust stand rotational axis in a consistent vertical orientation. Leveling adjustments were made with motor driven elevating screws underneath the stationary structure to an angular resolution of 1.5×10^{-5} degrees. Deflections of the torsional arm in response to PPT thrust were measured with a LVDT. The transformer coils are attached to the stationary structure and the iron core is attached to the torsional arm. Deflections up to 5 mm could be measured with a resolution of 5×10^{-4} mm using this setup. The deflection signal was displayed on a digital output and was fed into a strip chart recorder. Since the torsional spring-mass system was essentially frictionless, a derivative feedback loop was used to damp out unwanted thrust stand oscillation. The system was electromechanically operated and could be switched off in order to observe single pulse thruster performance. A steady-state force calibration arrangement was also contained in the stationary structure. The calibrator determined the overall spring stiffness of the thrust stand and was used as a reference by which all measurements were quantified. A

polyester fiber approximately 6 μ m in diameter was used to exert a known calibration force coincident with the thrust axis of the PPT. Three weights of 250 μ N each were strung on the fiber and fed over a fluorinated polymer pulley to pull on the arm. The free end of the fiber could be raised or lowered to engage each weight in tension underneath the pulley.

Figure 2 shows a chart recording of the thrust stand response to cycling the calibration weights. The thrust signal began in its equilibrium position until the first weight was applied. With the damper active, the thrust signal quickly stabilized at a higher level in response to a 250 μ N weight. This was followed one minute later by an additional 250 μ N weight. After the third weight was applied the process was reversed. As each weight was disengaged, the thrust signal dropped to a level nearly identical to the previous value. A small offset indicated hysteresis in the measurement, which was partly due to friction in the pulley. Hysteresis was typically less than 1 percent. Special effort was made to keep frictional forces to an absolute minimum, but pulley friction was unavoidable as long as there was tension in the fiber. This was of particular concern for single pulse measurements in which kinetic energy must be conserved very accurately. After the last calibration weight was disengaged the fiber went completely slack and pulley friction was no longer significant. Any remaining offset was caused by zero drift, which was often observed but usually less than 1 percent. The second half of Figure 2 shows how the thrust stand natural frequency was determined. With the damper circuit disengaged, the thrust stand was deliberately disturbed to set up an oscillation. Due to a lack of friction, the oscillation persisted for many minutes with the LVDT providing an accurate signal by which harmonic motion was observed. As shown in the figure, 31 oscillation cycles were recorded in 7 minutes for a ω_n of 0.464 radians per second.

Electrical power was transferred from the facility to the PPT through thrust stand electrical flexures. Two copper wires 0.76 mm in diameter and 250 mm in length were flexed in torsion to power the PPT. Four smaller 0.35 mm diameter copper wires were used to transfer control signals. A small loop was placed at each end of the wire in an effort to accommodate axial expansion and minimize thermal drift. A preliminary test was performed under vacuum conditions to determine thrust stand sensitivity to PPT input supply current. For this, the input terminal to the PPT was jumpered over, allowing current to be sent through the electrical flexure while the thrust stand was at rest. With the power supply turned on, a current of 3.0 A was sent through the electrical flexures while the thrust signal was monitored. Indicated thrust immediately began to drift slightly negative until it leveled off at a value of -3.5 μ N 2 minutes after current began flowing. Current was maintained at 3.0 A for several more minutes with no significant change. When current was turned off the thrust stand returned to its original zero within 3 minutes. While a similar drift in thrust signal may be expected as a result of

current drawn by the operating PPT, the error represents less than 1 percent of the total thrust.

Verification of Impulse Measurements

The first series of tests with the thrust stand were performed to verify that momentum data derived using eq(8) were accurately representing actual imparted values. This was done by striking the thrust stand with an impact pendulum. Momentum delivered by the pendulum was compared directly with the thrust stand response.

The impact pendulum consisted of a horizontal aluminum rod 2.4 mm in diameter and 15 cm in length. It was supported at each end by a nylon thread 0.5 m in length and was free to swing horizontally in a direction parallel to the axis of the rod, as shown in Figure 3a. The suspended mass of the pendulum was determined using a precision analytic balance and found to be 0.626 grams. The pendulum was suspended by a framework which aligned it in front of the PPT such that the impact point was dead center on the thruster. Since the impact tests were performed under vacuum conditions, the pendulum was manipulated by a lever arrangement using a rotary feedthrough.

The instantaneous speed of the pendulum was monitored by an optical arrangement, as was done similarly with the PET.⁸ A Ronchi ruling of 20 lines per cm was attached to the pendulum and oriented perpendicular to the path of motion, as shown in Figure 3b. A second similar Ronchi ruling was positioned to overlap the first but was attached to the stationary structure. As the two rulings moved relative to one another, the adjacent line patterns created an optical chopping effect which corresponded with periods of exact superposition and staggered overlap. This chopper frequency was monitored by placing an incandescent lamp and photo transistor on opposite sides of the adjacent rulings. As the pendulum swung down to impact the thruster, it cut through the optical path between the lamp and the photo transistor. The output signal from the photo transistor was recorded on a digital oscilloscope throughout the impact. The signal wave length was used to determine the chopper frequency. This frequency multiplied by the ruling line width determined the incoming and rebound speeds of the pendulum.

Figure 4 shows an oscilloscope trace of a typical pendulum impact. The sine wave on the left side of the trace represents the optical interrupt signal of the incoming pendulum immediately prior to impact. The frequency was 615 Hz, corresponding to a velocity of 0.312 m/s. At the center of the trace the pendulum underwent a partially elastic collision with the thrust stand. The pendulum changed direction and retraced its path at a reduced speed. The rebound frequency of the optical signal was 325 Hz, corresponding to a velocity of 0.165 m/s. The smaller amplitude of the incoming signal was believed to be caused by a poor electrical response of the photo transistor circuit at higher frequencies and should not affect the velocity data.

The momentum delivered by the pendulum was determined by adding the incoming and rebounding velocities, multiplied by the pendulum mass. In this case the total momentum delivered was 299 $\mu\text{N}\cdot\text{s}$.

Figure 5 shows a chart recording of the thrust stand response to the same pendulum strike. Prior to impact, the thrust stand was perfectly at rest in its neutral position. When the impact occurred the thrust stand nearly instantaneously accelerated to a finite velocity proportional to the momentum absorbed. Thrust stand displacement increased against a growing restoring force until a maximum amplitude was reached 3.4 seconds following impact. At this point the velocity dropped to zero, and the restoring force drove the thrust stand in the opposite direction. Since the spring-mass system of the thrust stand was essentially frictionless, it continued to oscillate until the electro-mechanical damper was activated. The thrust stand returned to its neutral position approximately 4 seconds after the damper was turned on. As can be seen, displacement amplitude was symmetric in the positive and negative directions, and was repeatable until the damper brought the system to rest. The maximum displacement used in eq(8) was measured as half the peak to peak amplitude shown in the chart recording.

The above procedure was performed with pendulum strikes at four different magnitude levels, and the results of these are shown in Figure 6. This is a plot of impulse measured with the thrust stand as a function of momentum delivered by the impact pendulum. The dotted line has a slope of 1, and represents an exact match. As can be seen, the impulse values measured by the thrust stand were nearly identical to those delivered by the pendulum, from the smallest impulse bit of 85 $\mu\text{N}\cdot\text{s}$ to a maximum of 412 $\mu\text{N}\cdot\text{s}$. The results presented in Figure 6 suggest that thrust stand deflection measurements combined with eq(8) should accurately determine individual PPT impulse bits over the range in which they commonly occur. No empirical correction factors were required. The largest contribution to overall uncertainty resides in the ability to determine thrust stand displacement. In most cases this is within 1 percent of the measured value.

PPT Single Shot Operation

The LES-8/9 thruster was first run in a single shot mode to determine the impulse bit of individual pulses. Tests were performed in a 1.5 m diameter by 5 m long vacuum facility¹⁰ at an ambient background pressure of approximately 2×10^{-3} Pa (1.5×10^{-5} torr). All single pulse momentum measurements were obtained by observing the thrust stand displacement with the damper disengaged. Procedures for operating the thrust stand and data acquisition equipment were identical to those used when testing with the impact pendulum. The thruster was provided with 28.0 V across the main input terminals using a laboratory power supply. A single PPT discharge could be obtained by applying a momentary ground signal on the control input

terminal. Figure 7 shows the thrust stand displacement signal resulting from a series of PPT single shot pulses, spaced about 45 seconds apart. Each trace began with the thrust stand at rest and the damper off. Once the thruster fired, the thrust stand almost instantaneously accelerated to a finite velocity determined by the mass of the thruster and the impulse bit delivered by the PPT. Displacement increased almost linearly with time, then gradually leveled off as the restoring force from the thrust stand decelerated the thruster. At the point of maximum displacement the thruster came to a complete stop and then reversed direction towards the thrust stand neutral position. Since there was no frictional damping the thruster overshot the neutral position resulting in a sinusoidal oscillation until the electromechanical damper was activated. When damped, the thrust stand quickly returned to its neutral position in preparation for the next pulse. As with the impact pendulum tests, maximum displacement was measured as half the peak to peak movement of the thrust stand resulting from the pulse. At the end of the trace in Figure 7 is a calibration resulting from a 250 μN weight pulling along the thrust axis.

Since the LES-8/9 thruster uses two discharge ports firing at 30 degrees to the mounting plane, all performance data was adjusted for the cosine loss resulting from an off-axis firing. Figure 8 is a plot of sequentially measured impulse bits obtained from the PPT and corrected for a 30 degree off axis thrust vector. The apparently random variation in performance is believed to be real. The fact that the discharge plume was visibly different from pulse to pulse provided some evidence of this. The average impulse bit obtained in the test sequence was 266 $\mu\text{N}\cdot\text{s}$. This value was slightly less than the 300 $\mu\text{N}\cdot\text{s}$ published as nominal performance for this device.¹¹ At the time of installation there was noticeable soot on the insulators and carbon scale on the electrodes. This may have resulted in poor current distribution within the discharge and could explain the performance difference.

PPT Repetitive Operation

The thrust stand was used to determine the time averaged thrust of the PPT operated in repetitive mode. This was possible because the thruster firing repetition rate was about 30 times the natural frequency of the thrust stand. Since the thrust stand response time was very long compared to the pulse repetition rate, it effectively averaged the continuous string of impulse bits into a uniform thrust force. The restoring force of the thrust stand increased linearly with distance from its neutral position, and eventually balanced the average thrust of the PPT. As with conventional steady-state thrusters, the thrust stand displacement was compared with deflections produced by free hanging calibration weights as a means of quantifying force measurements. Further smoothing of the average thrust signal was obtained by using the electromechanical damper described earlier. Since the damper was sensitive

only to velocity and not position, it resisted motion equally in both directions. The time average force imposed on the thrust stand by the damper is zero, and so steady-state force measurements were not affected.

The LES-8/9 thruster was tested in repetitive mode by maintaining a constant ground signal on the control input terminal. When this was done, the thruster automatically fired at about 2 Hz until the control signal was removed. Figure 9 shows a thrust signal of the PPT during repetitive pulsed operation. Before the thruster was activated the thrust stand was calibrated by cycling the weights as was done for Figure 2. When turned on, the initial thruster pulse pushed the thrust stand in the positive direction followed by a very brief coasting movement. Each successive pulse pushed the thrust stand farther away from its neutral position as the restoring force began to pull in the opposite direction. After a period of time comparable to the natural time constant of the thrust stand, an equilibrium position was reached. Pulse induced fluctuations of the thrust stand were typically about 1 percent of the steady-state value. Pulse frequency was counted at various points throughout the test run and found to be consistently 132 per minute. Irregular performance of the thruster resulted in sporadic excursions of the thrust signal which were typically several seconds in duration. These excursions are clearly visible in the thrust signal and result in variations of as much as 10 percent the average steady-state value. Average thrust was measured to be approximately 496 μN during the entire 30 minutes of operation. When taking the thrust vector loss into account, this translated to a thrust of 573 μN along the axis of the discharge port. It is noteworthy that this value did not increase or decrease appreciably over the course of the test. When the thruster was turned off the thrust signal immediately dropped but was slowed in decent by the damper, resulting in a slight overshoot. After several seconds the thrust zero returned very nearly to its original position, with less than 1 percent positive drift. It may be noted that the zero drift observed after actual thruster operation was in the positive direction while the drift observed during electrical flexure shunt tests was in the negative direction. The current drawn by the PPT during repetitive operation averaged 1.75 A, which was less than the 3 A used in the flexure test. Clearly there are other mechanisms than just input current which influenced the drift of the thrust signal. The consequence of zero drift was that it added uncertainty to thrust measurements taken mid-way through the test run. Measurements taken at the beginning or end were considered more accurate because they occurred immediately after or before a recent thrust zero, and were easily corrected. Since there was no more than 1 percent zero drift during the course of this 30 minute test, it is reasonable to assume that the uncertainty of thrust measurements taken in the middle was about 1 percent.

An important quantitative comparison can be made between the results obtained from the single shot thruster operation with that obtained in repetitive mode. The total impulse exerted by the thruster during repetitive operation was determined by the average thrust integrated over time.

A thrust of 573 μN for 30 minutes resulted in a total delivered impulse of 1.03 N-s. During this period, the thruster fired approximately 3960 times. Thus, the average impulse bit per pulse was approximately 260 $\mu\text{N-s}$. This compares closely with an average single shot value of 266 $\mu\text{N-s}$ measured from individual pulses. A more qualitative comparison can be made by examining the time dependent variations in PPT performance. The thrust excursions observed in Figure 8 during the repetitive operation were consistent with the shot to shot variations seen in Figure 8. While there appeared to be localized patterns during the excursions rather than pure random variation, a larger sample of single shot pulses may be required to identify similar statistical groupings.

Conclusions

A torsional type thrust stand has recently been built for the purpose of testing PPTs in both single shot and repetitive operating modes. Momentum per pulse was determined strictly as a function of thrust stand deflection, spring stiffness, and natural frequency. No empirical corrections were needed. The accuracy of this method was verified using a swinging impact pendulum. Momentum transfer data between the thrust stand and the pendulum were consistent to within 1 percent.

A LES-8/9 PPT was tested on the thrust stand. It had a mass of approximately 7.5 kg, with a nominal thrust to weight ratio of 1.3×10^{-5} . A total of 34 single shot thruster pulses were individually measured. The average impulse bit per pulse was 266 $\mu\text{N-s}$, which was less than the value of 300 $\mu\text{N-s}$ published in previous reports on this device.

Repetitive pulse measurements were performed in a way similar to ordinary steady-state thrust measurements. The thruster was operated for 30 minutes at a repetition rate of 132 pulses per minute and yielded an average thrust of 573 μN . Based on thrust measurements, the average impulse bit per pulse was estimated to be 260 $\mu\text{N-s}$. Zero drift after this time was found to be about 1 percent of the measured thrust.

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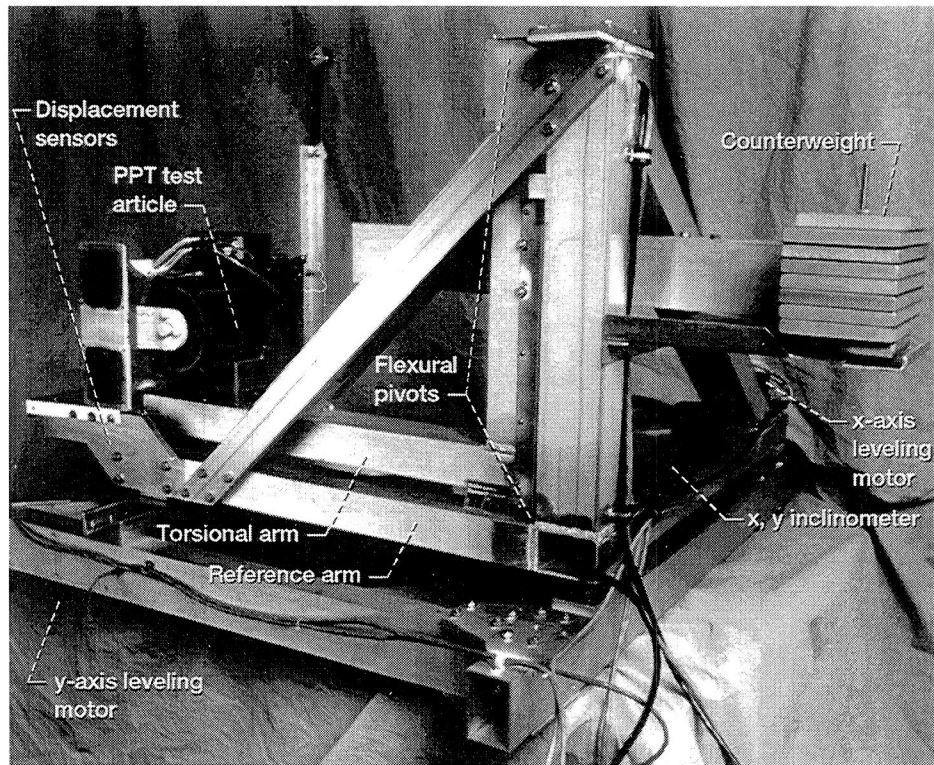


Figure 1.—Photograph of thrust stand.

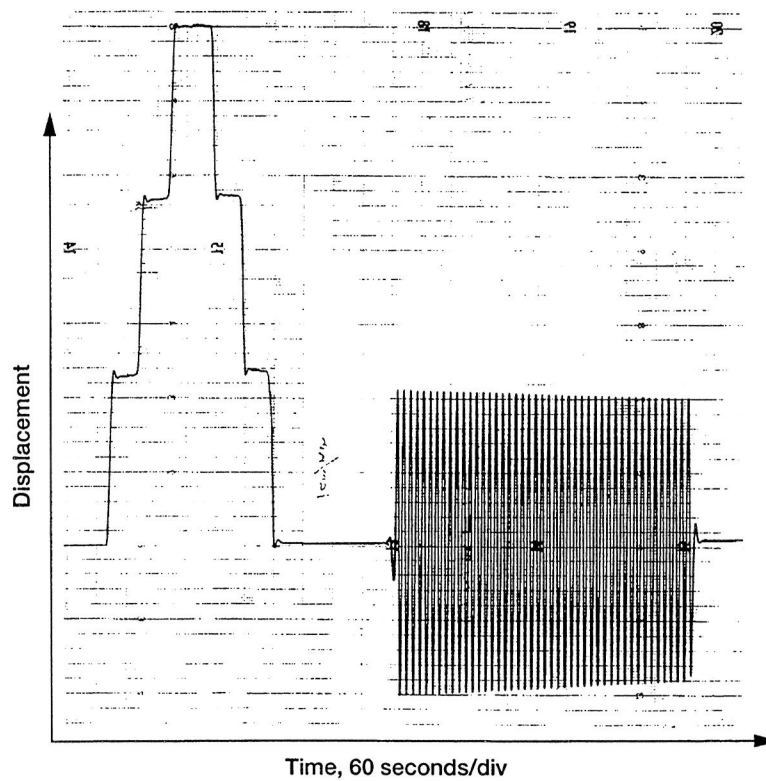


Figure 2.—Thrust stand displacement during calibration cycle.

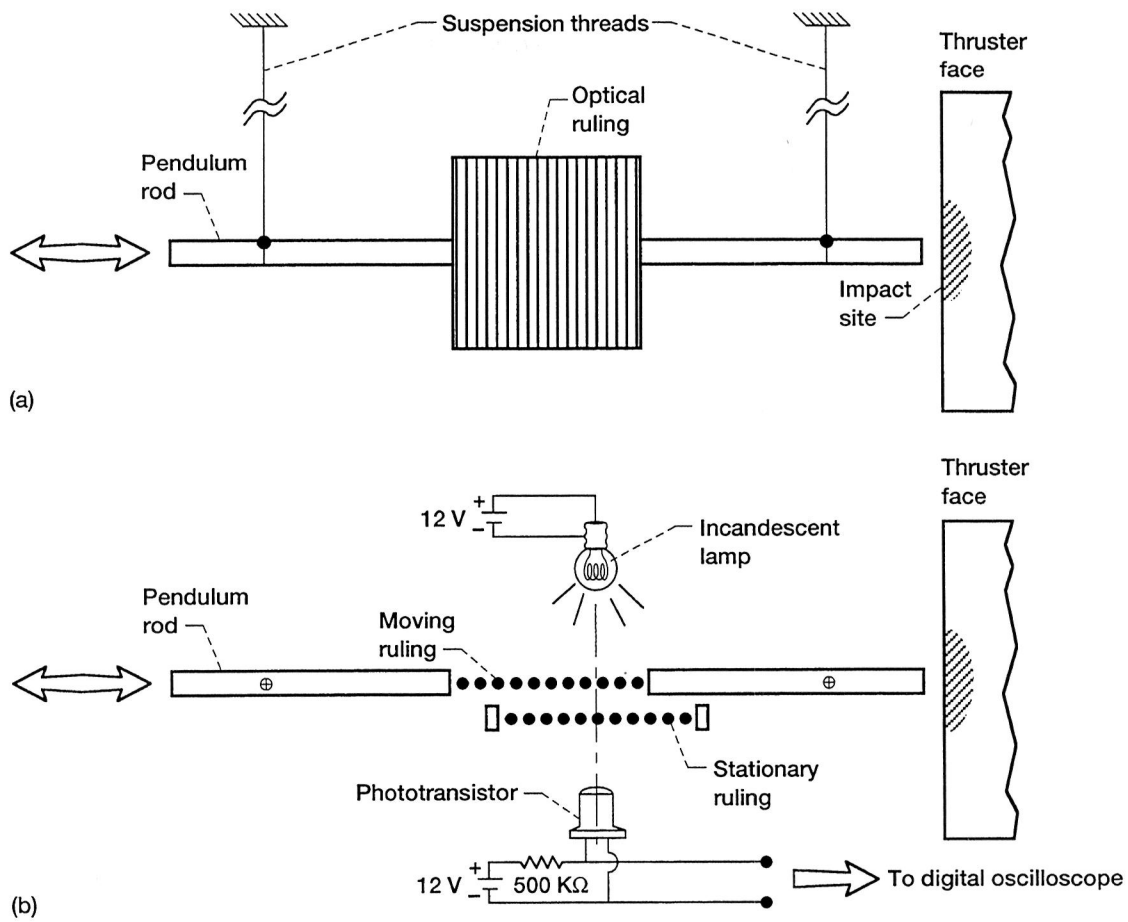


Figure 3.—Diagram of impact pendulum. (a) Side view. (b) Top view.

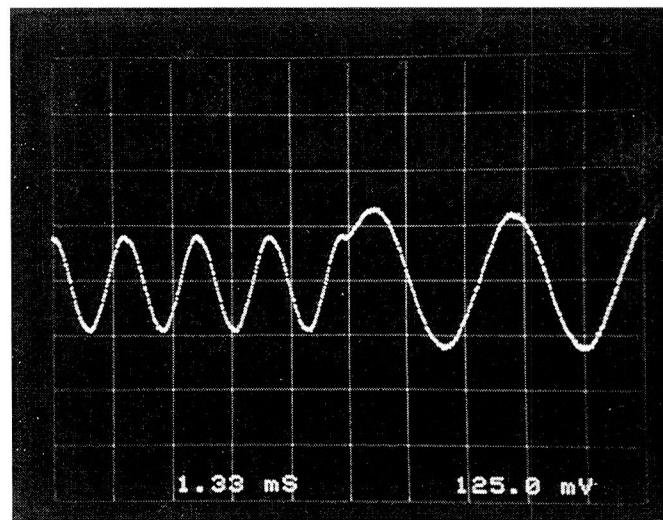


Figure 4.—Output signal from photo transistor during pendulum strike. Time scale (1.33 μ s/div).

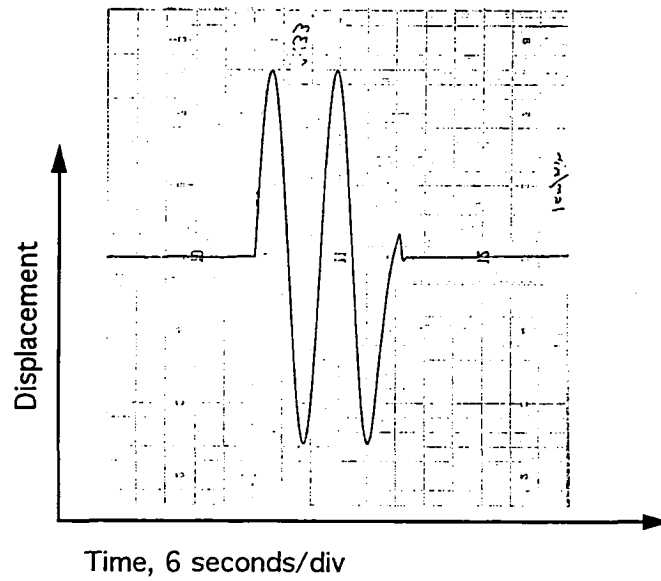


Figure 5.—Thrust stand response to pendulum strike.

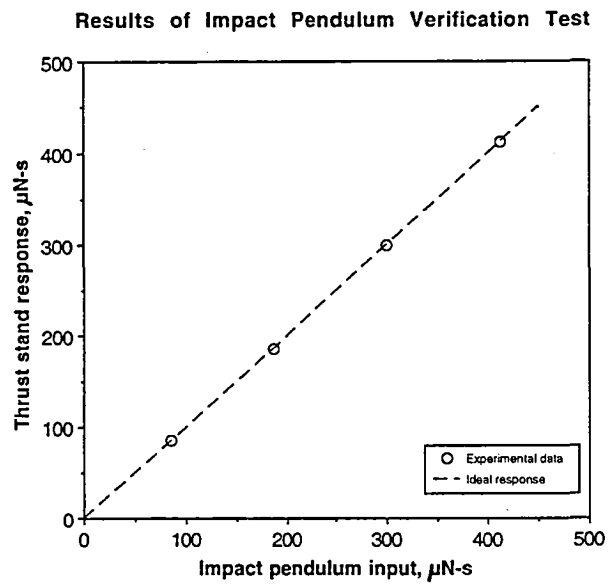


Figure 6.—Plot of impact pendulum verification results.

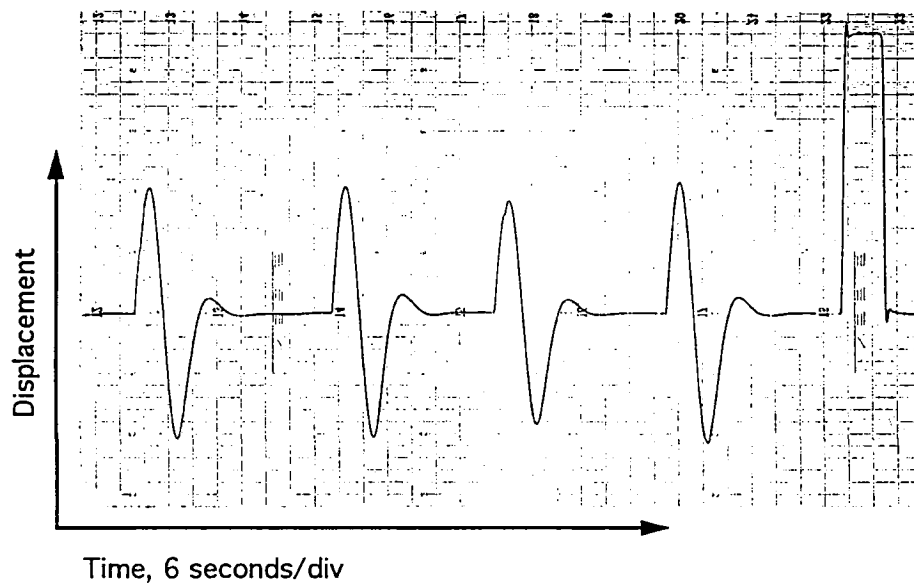


Figure 7.—Thrust stand response to series of PPT pulses.

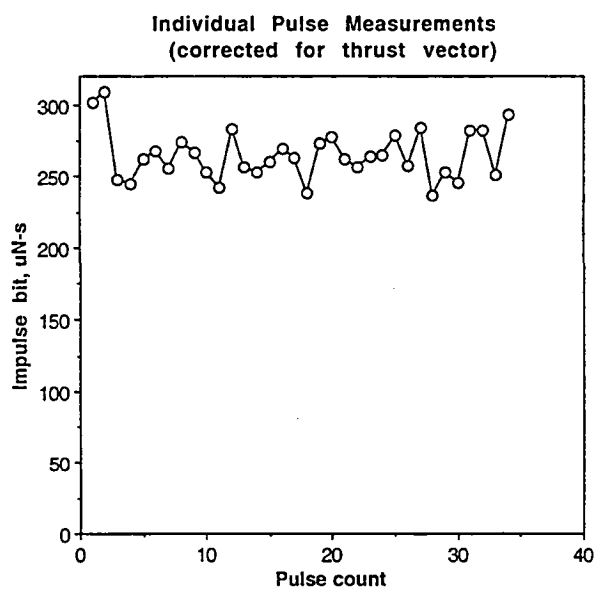
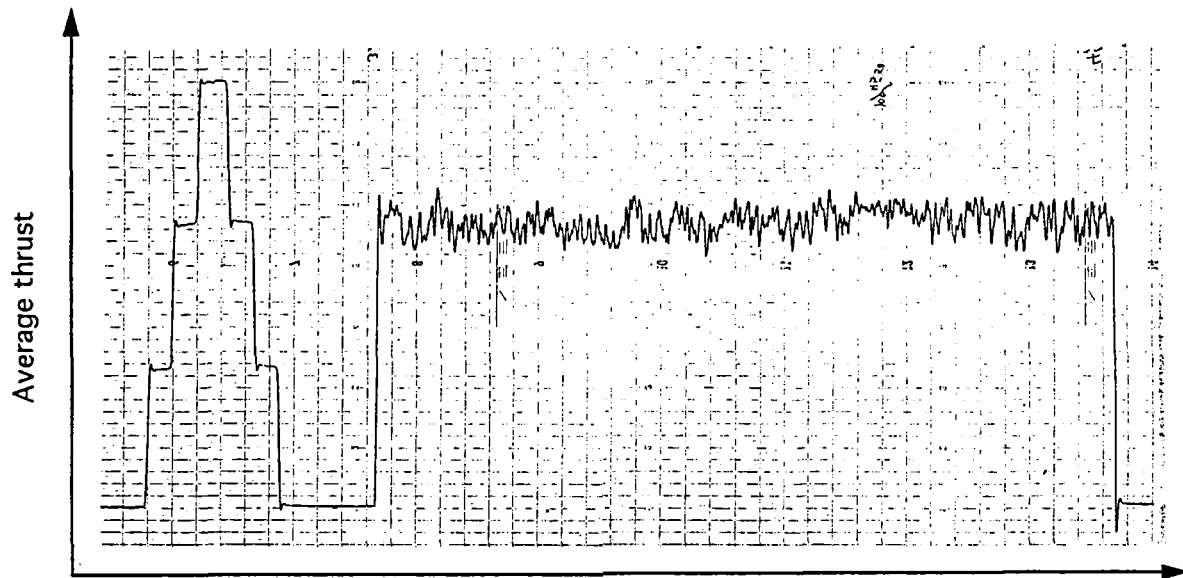


Figure 8.—Momentum measurements of individual PPT pulses.



Time, 60 seconds /div

Figure 9.—Average thrust of PPT at 132 pulses/minute.

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13. ABSTRACT (Maximum 200 words) A torsional-type thrust stand has been designed and built to test Pulsed Plasma Thrusters (PPTs) in both single shot and repetitive operating modes. Using this stand, momentum per pulse was determined strictly as a function of thrust stand deflection, spring constant, and natural frequency. No empirical corrections were required. The accuracy of the method was verified using a swinging impact pendulum. Momentum transfer data between the thrust stand and the pendulum were consistent to within 1 percent. Following initial calibrations, the stand was used to test a Lincoln Experimental Satellite (LES-8/9) thruster. The LES-8/9 system had a mass of approximately 7.5 kg, with a nominal thrust to weight ratio of 1.3×10^{-5} . A total of 34 single shot thruster pulses were individually measured. The average impulse bit per pulse was $266 \mu\text{N-s}$, which was slightly less than the value of $300 \mu\text{N-s}$ published in previous reports on this device. Repetitive pulse measurements were performed similar to ordinary steady-state thrust measurements. The thruster was operated for 30 minutes at a repetition rate of 132 pulses per minute and yielded an average thrust of $573 \mu\text{N}$. Using average thrust, the average impulse bit per pulse was estimated to be $260 \mu\text{N-s}$, which was in agreement with the single shot data. Zero drift during the repetitive pulse test was found to be approximately 1 percent of the measured thrust.				
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