Pulsed Thrust Measurements Using Laser Interferometry*

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Abstract

The final design of an optical Interferometric Proximeter System (IPS) for measuring the thrust of pulsed thrusters, in particular pulsed plasma thrusters, has been completed. This paper reports the recent improvements of the IPS and reviews the basic principles. Unlike existing thrust stands, the IPS-based thrust stand offers the advantage of a *single* system that can yield EMI-free, high accuracy ($< 2\%$ error) thrust measurements within a very wide range of impulses (100 μN-s to above 10 N-s) covering the impulse range of all known pulsed plasma thrusters. At very low thrust levels the IPS becomes ideally suited for measuring the performance of *steady state* thrusters such as the FEEP thruster. The IPS is capable of measuring steady state thrust values as low as 10 μN-s. The IPS-based thrust stand relies on measuring the dynamic response of a swinging arm using a two-sensor laser interferometer with 10 nm position accuracy. The wide application of the thrust stand is demonstrated with thrust measurements of an ablative pulsed plasma thruster (APPT) and a gas-fed Magnetoplasmadynamic (MPD) thruster. The LES 8/9 APPT average mass bit and efficiency are presented. Lastly, a power spectrum method is presented for maximizing the signal to noise ratio of the experiment.

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1 Introduction

The performance of many steady-state electric thrusters improves as the operating power level is increased. Due to the limited available power in most foreseeable missions, instantaneous pulsed high power provides better performance while requiring low average power levels. Pulsed plasma thrusters, such as the ablative pulsed plasma thruster (APPT) are currently the only viable high specific impulse propulsion options on small spacecraft with available power levels less than 200 W. The mass savings advantage[1, 2] pulsed plasma thrusters offer to many near-term power-limited small satellites has renewed interest in these devices and consequently in the accurate measurement of their performance. The most critical performance measurement is that of thrust.

In addition to pulsed plasma thusters, there is one electric steady state thruster that can operate at arbitrarily low power levels: the FEEP thruster. The FEEP thruster operates in the very low thrust regime near 100 μN.

Aside from short pulse thrusters, there is a need to study the performance of quasi-steady pulsed thrusters which are used in the laboratory as a simulation of steady-state high power thrusters that are intended for more futuristic high-power (MW-level) missions. For such thrusters the requirement is not only to measure the total impulse but also to resolve the thrust *during* the pulse in order to estimate the equivalent steady-state thrust. Vibrations within the thruster have so far precluded such a measurement[3].

Although diagnostic methods already exist for impulse bit and instantaneous thrust measurements of various magnitudes, no *single* high-accuracy diagnostic is known to measure impulse values throughout the entire operating range of typical PPTs, and resolve the thrust of quasi-steady pulsed plasma devices[3]. An optical interferometric proximeter system (IPS) was designed to meet these needs while providing other advantages.

All experiments were performed in the Pulsed High-Power Performance facility at EPPDyL. The vacuum equipment, MPD power supply, thrust stand design, and a detailed description of the IPS are described in reference [3] with the exception that the thrust stand is now mechanically isolated from the tank by resting the entire structure on rubber supports.

2 Performance Measurement Fundamentals

2.1 Thrust and Impulse Bit

Performance measurements for a given thruster will rely on one of two different values: the total delivered impulse or the average thrust. Both are done via the measurement of the thrust stand dynamics. The impulse bit measurement involves measuring the velocity before and after a thruster pulse (Δv). An average thrust measurement involves either a Δv measurement or a steady state deflection of the thruster arm.

2.2 Thrust Stand Dynamics

Thrust stand systems can be treated like a "black box." The input to the system is the applied thrust and the response of the system can be observed from many locations within the thrust stand system. The exact dynamic response of each observation point on a thrust stand to a given thrust input can, in general, be complex. Fortunately, in many cases the thrust stand can be modeled with a high degree of accuracy as a damped spring-mass system. If the motion of the observation point is characterized by x, and the effective natural frequency, damping constant, and mass are $\omega_{n,eff}$, ζ_{eff}, and m_{eff} respectively, the applied impulse bit (I_{bit}) will force the response[4]

$$x(t) = e^{-\zeta_{eff}\omega_{n,eff}t}\frac{I_{bit}/m_{eff}}{\omega_{n,eff}\sqrt{1-\zeta^2}} \sin\left(\sqrt{1-\zeta^2}\omega_{n,eff}t\right). \quad (1)$$

The duration of the impulse must be much less then the natural period of the observation point for equation 1 to be valid. In many of such cases, measurements can be made on time scales where the effects of the spring and damper are negligible. In the absence of a spring and damper, this model leads to the simple momentum equation,

$$I_{bit} = m_{eff}\Delta\dot{x}, \quad (2)$$

where $\Delta\dot{x}$ is the change in velocity of the observation point from before to after the impulse. In order to compute the impulse bit , a calibration constant, the effective mass (m_{eff}), for the IPS must be determined. This can be done by applying a known impulse to the system and observing the dynamic response. This is discussed in section 2.3.2. Whether the appropriate model is this simple or not, the position coordinate provides the dynamic response of the system to an excitation. The IPS was designed around this idea and can provide continuous position data with accuracy as high as 10 nm[3].

2.3 Thrust Stand Position Measurement with the IPS

2.3.1 IPS Setup

At the thruster end of the tank the IPS table top was mounted at the optical access window. Figure 1 is a layout of the IPS used at the PHPP facility. One corner cube is attached to the thrust stand table and the other to the thruster. A 1 mW Helium-Neon laser was used for which λ=632.8 nm. Both the beam splitter and the right angle prism were mounted on two adjoined aluminum blocks with separate pitch angle adjustment. Also the beam splitter and right angle prism can each slide sideways to match the horizontal separation of the corner cubes. Both of these adjustments are made until both beams are coincident at the adjustable mirror. The mirror is then used to direct the beams to the diode sensors. Between the mirror and the diodes are a lens and a filter. The lens is a cylindrical lens of focal length 1 cm. This expands the beams in one dimension and facilitates the production of multiple fringes while keeping the intensity of light which is incident on the diodes at a maximum. Finally there is a 3 nm bandwidth filter at wavelength 632.8 nm. This prevents virtually all of the stray light from the surroundings from reaching the diode sensors, including light from the plasma discharge.

2.3.2 The IPS Calibration Constant: m_{eff}

Once two corner cube locations have been chosen for the relative x measurement, the effective mass (m_{eff}) must be determined. This process is synonymous with calibrating the IPS. A known impulse

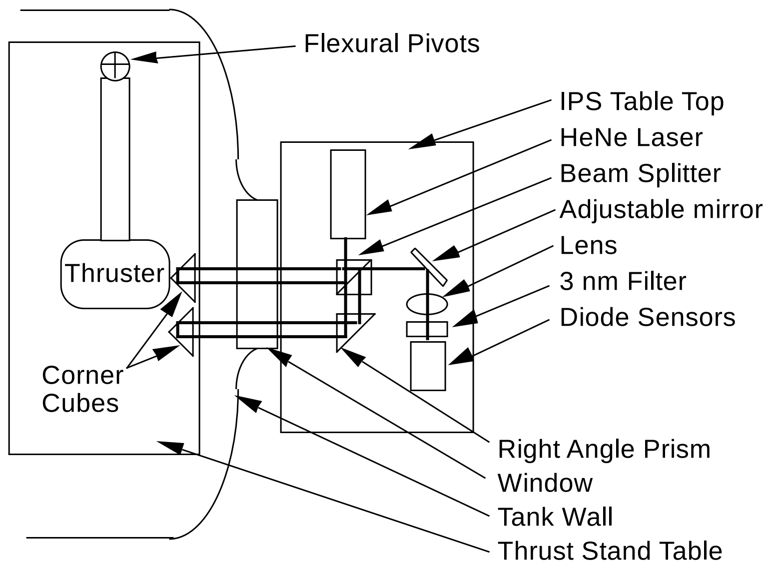

Figure 1: IPS layout at the PHPP facility

must be given to the thrust stand while the response is recorded by the IPS. The impulse must be applied at the same location as the force which is applied during an actual firing of the thruster. A commercially available force transducer provides a simple way of applying a measurable impulse. The thruster must be struck with the force transducer while the force transducer output voltage is being recorded. Integrating the force with respect to time yields total impulse. The IPS should record the response of the thrust stand to the impulse. From the measured change in velocity (Δv), the effective mass can be determined using the measured total impulse for I_{bit}:

$$m_{eff} = \frac{I_{bit}}{\Delta v} \tag{3}$$

A 30 cm long 0.5 kg steel rod was used as a pendulum (See figure 2). The rod pivots on a teflon pin which was fixed to an aluminum stand. This stand was mounted inside of the vacuum tank in front of the thruster. An electromagnet was also mounted on the pendulum stand so that the pendulum could be cocked and then released remotely. Care must be taken to align the pendulum so that the force is delivered along the thrust axis[3].

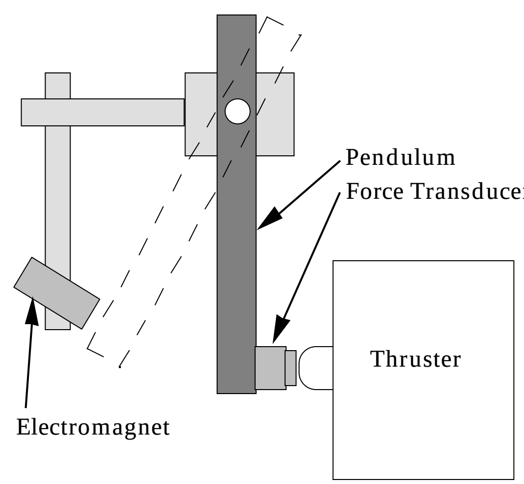

Figure 2: Pendulum for m_{eff} calibration

3 Experimental Results

3.1 APPT Performance Measurement

The APPT used for this experiment is the Lincoln Experimental Satellite thruster (LES-8/9). The APPT has a mass of 6.6 kg and has a total impulse capability of 7320 N-s[5]. The impulse bit is nominally 300 μN-s and the specific impulse is 1000 s. The PFN is internal and requires an external 25-150 watt power supply to charge the main 17 μF oil-filled capacitor. The pulse lasts for 2-5 μs and can pulse at a maximum of 2 Hz. The discharge occurs across the surface of a Teflon fuel bar and ablates approximately 30 μg of propellant. There are two nozzles canted at 30 degrees to the thruster axis of symmetry. This APPT will fly on IZMIRAN's COMPASS satellite in October 1996. For these experiments only one nozzle was fired. The APPT was mounted on the thrust stand such that the nozzle was perpendicular to the thrust arm.

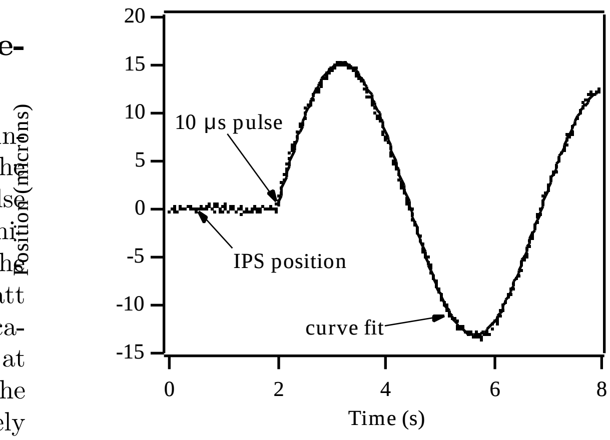

Figure 3: IPS position data with curve fit

3.1.1 Impulse Bit

On short time scales, the free-mass model for impulse bit calculations is always valid. However, it may be that the background noise disallows accurate $\dot{x}$ measurements to be made. In this case the second alternative is to observe longer time scales and model the system with more complexity. In the case of a damped spring-mass system Eqn. 1 describes the dynamic response. Using the force transducer method described in section 2.3.2 the effective mass was determined. An insert was made to fit into the nozzle. The calibration pendulum struck the center of the insert. The result was m_{eff} =12.16 kg. The IPS configuration for the APPT experiments was also as shown in figure 1. For small damping, the maximum displacement (Δx) for this system is

$$\Delta x = \frac{2I_{bit}}{\omega_{n,eff} m_{eff}}. \qquad (4)$$

Therefore, restoring forces on the thrust arm were minimized such that $\omega_{n,eff}$ was minimized and the resultant displacement was maximized. Once the effective mass is known the position data from a damped spring-mass system can be fit to the model. Eqn. 1 requires ζ_{eff}, $\omega_{n,eff}$, and I_{bit} for a fit. Figure 3 shows the raw, unfolded double IPS sensor position data and the curve fit. A small correction was made to each curve fit value for the impulse bit based on the initial velocity (always < 1% of the impulse bit). The impulse bit was found to be 285 ± 5 μN-s.

3.1.2 Efficiency

The efficiency (η) of the APPT is given by

$$\eta = \frac{I_{bit}^2}{m_{bit} C V^2} \qquad (5)$$

where m_{bit} is the mass ablated per shot, C is the capacitance of the capacitor, and V is the capacitor voltage prior to the discharge. The mass bit was measured by firing 436 pulses and measuring the lost mass in the Teflon propellant bar. This entire procedure resulted in an average mass bit of 34.77$\pm$0.24 μg and an efficiency calculation of 6.8 $\pm$0.27%.

3.2 Measuring the Performance of FEEP Thrusters

Recent interest in the FEEP thruster is accompanied by the desire to accurately measure its thrust performance. These thrusters are typically designed in the 100 μN thrust range[6]. As described in section 4.2, the low frequency operation of the IPS can easily detect motion in the micron regime. Section 3.1 demonstrates this with the LES 8/9 APPT. Assuming that the thruster mass[6] and mounting hardware is approximately 3 kg, a 100 μN thrust left on for 1 s will cause a displacement of approximately 15 μm. This will easily be detected by the IPS and will allow a thrust measurement to be made.

Smaller trust levels can be accommodated as well. As the thrust level drops, the thruster must be left on for a longer time to produce a measurable displacement of the thrust arm. As this amount of time becomes comparable to the natural period of the thruster arm, it cannot be considered as an impulsive event for the damped sinusoidal model (see Eqn. 1). In this case, a steady state displacement method can be used. The effective spring constant on the thrust arm (k_{eff}) is easily determined from the information in section 3.1 as

$$k_{eff} = m_{eff}\omega^2 \approx 20\mu N/\mu m. \qquad (6)$$

This indicates that a 20 μN thruster will produce a steady state displacement of the thrust arm of 1 μm, a distance within the measurement capability of the IPS. Recently, by carefully aligning the thruster arm to a nearly horizontal position, the effects of gravity, which contribute to k_{eff}, have been further reduced to yield a $k_{eff} \approx 10$ μN/μm. It is therefore estimated that the IPS can measure steady state thrust levels as low as 10 μN.

3.3 Gas-fed MPD Performance Measurement

This section describes the use of the IPS to measure impulse bit for the a benchmark configuration coaxial gas-fed MPD thruster. This thruster has a 12.7 cm diameter anode with a 10 cm long hemispherically tipped, 1.9 cm diameter cathode. This thruster has a 5 cm deep chamber and an anode inner radius of 5.1 cm. Propellant injection is at the back plate of the chamber. Argon at 6 g/s was used. For one pulse of the thruster, the mass flow lasts for approximately 20 ms during which is a 1.5 ms current pulse of approximately 15 kA. The operating voltage is a nominal 100 volts. The experimental equipment used for this experiment is described in reference [3].

The most convenient model of the thrust stand system to use with the pulsed gas-fed MPD thruster is the free-mass model. In this case Eqn. 2 is employed. With the IPS calibration constant for this thrust stand arrangement, the pulsed gas-fed MPD the delivered impulse was found to be $91 \pm$ 1.6 mN-s

4 Error Analysis

4.1 Error in m_{eff} and the Curve Fit Values

Each final impulse value was comprised of a m_{eff} measurement and a value from a curve fit. The m_{eff} error was found to be 1.7%[3]. The error associated with the curve fit values is estimated from a statistical approach by the curve fitting software. For the presented results, all curve fit values had error $< 1\%$ and the background acceleration noise was < 0.06 m/s[3].

4.2 IPS Signal to Noise Ratio: Choosing a Measurement Technique

The IPS is capable of measuring position data throughout a wide range of frequency and amplitude. Since the IPS can be used in different ways to measure the same thruster performance value (i.e. Δv measurement, steady state thruster arm displacement measurement, or damped sinusoidal fit) it is necessary find a way of choosing the best technique. This can be done by considering the power spectrum of the background noise.

The power spectrum of the background noise indicates which of the various measurement techniques should be used to obtain a thrust measurement. One must first calculate what ideal response of the thruster arm is expected from the predicted impulse. For instance, for the sinusoidal response, the strength of the signal expected at the arms natural frequency (as in figure 3) can be compared to the background noise. This will give a signal to noise value and can be compared to other techniques. If needed, a band pass filter can be applied to the raw IPS data to eliminate background noise before the curve fitting process is begun. Each technique should be considered and the one with the highest signal to noise ratio will provide the most accurate measurement. For instance, for the LES 8/9 APPT, figure 4 shows the background noise, a curve indicative of the damped sinusoidal response of the arm, and a sine wave indicative of the type of signal one would need to measure if a ΔV measurement were to be done, which must be performed on a time scale much shorter then the natural period of the thruster arm. Figure 5 shows the Fourier Transform of the background noise. In the same units, a Fourier Transform of the ΔV curve has a value of about 400 at about 0.8 Hz while the damped sinusoid has a value of about 5000 at 0.1 Hz. Comparing

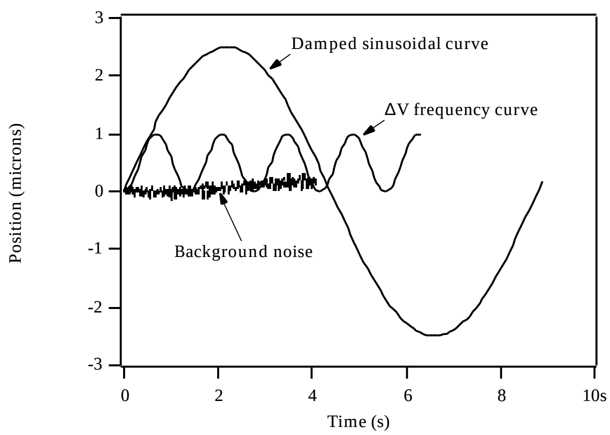

Figure 4: Position curves and expected signals

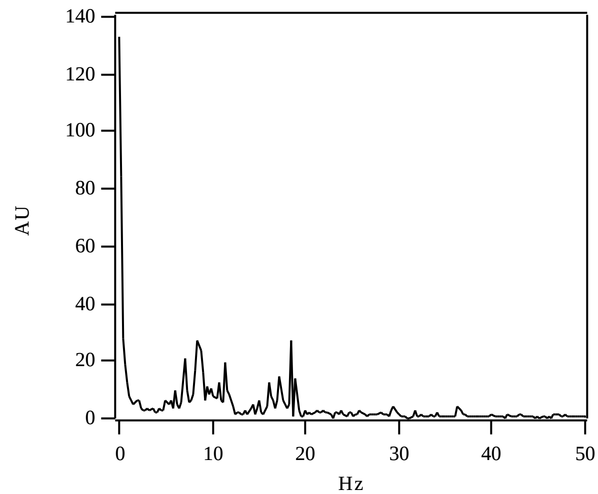

Figure 5: Fourier Transform of background noise

this to the respective noise values on figure 5 tells us that the damped sinusoid will give a better signal to noise ratio. In this case both techniques can provide a good measurement, but future work with lower impulse bit thrusters will benefit more from this tool.

5 Conclusions

An optical Interferometric Proximeter System (IPS) for measuring the thrust of pulsed thrusters, in particular pulsed plasma thrusters, has been designed and developed. The IPS has demonstrated the ability to accurately measure pulsed thruster performance for thrusters in the range of 1×10^{-4} N-s and 0.1 N-s nominal impulse values to an accuracy of <2%. The measured impulse bit for the LES 8/9 APPT, due to be launched in mission COMPASS P^{3}OINT, was 285±5 μN-s and the measured impulse bit for the pulsed gas-fed MPD was 91±1.6 mN-s. The average mass bit and efficiency for the LES 8/9 APPT were found to be 34.77 ± 0.24 μg and 6.8±0.27%. It has also been determined that the IPS can measure thrust levels down to 10 μN, a range that includes most FEEP thrusters.

References

[1] R.M. Myers and S.R. Oleson. Small satellite electric propulsion options. In *29th Intersociety Energy Conversion Engineering Conference*, Monterey, California, August 7-11 1994. AIAA 94-4137.

[2] E.Y. Choueiri. A system optimization model for the application of ablative pulsed plasma thrusters to stationkeeping missions. In *30th Joint Propulsion Conference*, Indianapolis, Indiana, June 27-29 1994. AIAA 94-3392.

[3] E.A. Cubbin. Laser interferometry for pulsed plasma thruster performance measurement. In *24th International Electric Propulsion Conference*, Moscow, Russia, Sept 1995. IEPC 95-195.

[4] W.T. Thomson. *Theory of Vibrations With Applications.* Prentice-Hall, 1993.

[5] R.J. Vondra and K.I. Thomassen. Flight qualified pulsed electric thruster for satellite control. *Journal of Spacecraft and Rockets*, 1974. Vol. 11, No 9.

[6] M. Andrenucci. Pulsed feep:new experimental results. In *24th International Electric Propulsion Conference*, Moscow, Russia, Sept 1995. IEPC 95-97.