

Thermal Effects on Inverted Pendulum Thrust Stands for Steady-state High-power Plasma Thrusters

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AIAA-2003-4842§

July 22, 2003

Abstract

Thermal effects on direct measurements of the thrust produced by steady-state, high-power (≥ 10 s of kW) plasma thrusters using inverted-pendulum thrust stands are addressed. Three major sources of systematic error exist in the determination of thrust using an inverted-pendulum thrust stand; tare forces, thermal drifts, and thermal deflections. It is shown that thermal deflections, due to changes in the temperature of the flexures used to carry the thruster current, can be the most significant of these effects. The response of the flexural elements to changing thermal loads can produce stand displacements on the order of the expected thrust (100s of mN at thruster currents of 300-500 A). Thermal deflections were reduced by at least 80% by conducting the thruster current to the stand via mercury pots rather than the flexural elements.

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§Presented at the 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 20-23rd July, 2003, Huntsville, AL. Copyright by authors.

1 Introduction

In the study of steady-state, high-power plasma thrusters, the direct measurement of thrust is one of the most important and difficult measurements to obtain. The low continuous thrust levels characteristic of these thrusters, the electrical and cooling requirements for steady-state, high-power operation, and the intense thermal and electromagnetic environments in which they operate put many constraints on thrust measurements. Our thrust stand design is based on the concept of an inverted-pendulum following the work of Haag [1]. In previous work,[2], [3], we have presented the details of our variation on this design including an *in-situ* calibration method to determine stand sensitivity under experimental conditions, an *in-situ* method of correcting for tilt (i.e. maintaining stand vertical position), and a laser based system of measuring stand displacement[3].

Experience with this inverted-pendulum design has led us to separate the sources of thrust measurement error into three groups:

- Thermal drifts
- Tare forces
- Thermal deflections

Each of these will be described in detail in this paper. In our last work [3], we dealt mainly with the first two items. The thermal drifts were handled by the method of data collection and analysis. Some modifications to the data analysis procedure will be presented to further reduce this error. Tare force measurements were also made. The forces measured were found to be on the order of the thrust and were difficult to characterize. Additional experiments and calibrations have led us to believe that what we measured was not a true tare force, but rather due to large thermal deflections (item 3) of the stand. The reduction of these thermal deflections is the major focus of this paper.

The thrust stand design will be reviewed in Sec. 2. We will then discuss the three sources of measurement error in greater detail in Sec. 3. In Sec. 4, we review the calibration procedure for determining sensitivity and tare forces and present improvements to our method of analyzing the data in the presence of thermal drifts in stand position. The evidence for unacceptable thermal deflections of the stand, modifications to the thrust stand design to reduce these thermal deflections, and the results of these modifications are presented in Sec. 5.

2 The Inverted Pendulum Thrust Stand

Unlike a standard pendulum, in which it takes a larger force to move a heavier mass through the same deflection angle, an inverted-pendulum takes advantage of the weight of the thruster to amplify the deflection due to the applied force. For small deflections:

$$d = \frac{FL}{g[M_\star - M]} \quad (1)$$

where d is the horizontal stand displacement, F the total force applied to the stand, L the length of the flexures, M the mass supported by the stand and M_\star is a characteristic mass which depends upon the stand characteristics. M_\star is defined as:

$$M_\star \equiv Lk/g \quad (2)$$

where k is the effective spring constant, or elasticity, of the stand flexures. Stand displacement is directly proportional to the applied force. As will be seen later, we measure the change in the *angle* of the stand tilt, not the stand displacement. Because of the small angles of deflection we can assume a linear relation between force and angle and this was verified by the calibration.

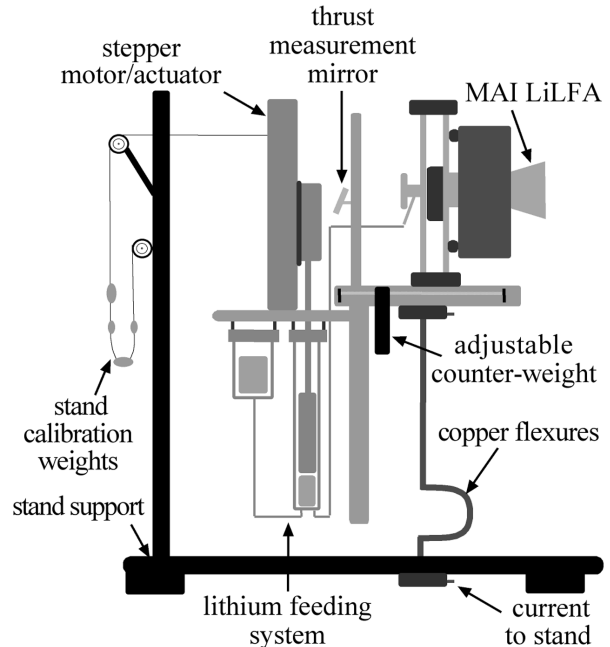


Figure 1: The schematic of the inverted-pendulum thrust stand, plasma thruster and lithium feed system.

2.1 Thrust Stand Description

Our implementation of the inverted-pendulum design of Haag [1] is shown schematically in Fig. 1. Our initial stand design is described in [2]. There are two primary components of the thrust stand: 1) the flexures that serve as the pendulum arm and support and 2) the aluminum support structure for the thruster and subsystems. The pendulum arm consists of nine parallel “b” shaped 3/8” diameter copper tubes. The flexures are held in place at their base by a fiberglass

beam attached to the vacuum chamber. Thin (5 mil), 5 cm wide sections of flexural brass sheet attached to either side of the main flexures limit stand twisting. The aluminum support structure is mounted to the top of the flexures by another fiberglass beam. The copper flexures fulfill three important purposes:

- Support and serve as the pivot point of the thrust stand.
- Conduct electrical power for the thruster components and subsystems.
- Carry cooling water to the thruster and subsystems located on the stand.

We will see in this paper, that this triple use of the flexures, while the basis of many of the benefits of the inverted-pendulum design, make it susceptible to thermal changes on the time scale of thrust measurement. These temperature variations may cause significant stand deflections during steady-state, high-power thruster operation .

2.2 Laser-based Deflection Measurement

Our laser-based method for measuring the displacement of the stand was described in detail in [3]. For completeness a schematic of the set-up is provided here (Fig. 2). Briefly, a laser beam from outside the facility is deflected by a mirror on the thrust stand to a 2-D photodiode array (Photo-Sensing Device (PSD)). The location of the beam on the sensor is given as a voltage output and is independent of the intensity of the beam. The change in the angle of the stand is thus measured as a displacement of the laser beam at the sensor. The important point here is that the change in position of the beam is given as a voltage output and stand sensitivity is reported in mV/mN.

2.3 Force Measurement

Inverted-pendulum thrust stands determine thrust by measuring the change in position of the stand as

the thruster is turned off. Steady-state thrusters require many minutes to reach their operating conditions making it difficult to determine the change in force on the stand over that time period. It is much easier to determine that steady-state operation has been reached and then terminate the firing, monitor the stand deflection due to the *removal* of thrust force. The thrust is then determined from this change in stand position, the sensitivity of the stand, and the accounting for any tare (non-thrust) forces acting on the stand. The procedure for determining stand sensitivity and measuring tare forces will be described in Sec. 4.

3 Sources of Error in Thrust Measurements

Now that we have described the thrust stand design we are in a better position to examine the sources of thrust measurement error in detail.

3.1 Thermal drifts

We define these drifts as slow changes in the stand position that occur over the course of the entire experiment. They are caused by changes in the thermal environment of the stand, largely due to radiation from the thruster and its components. Unlike thermal deflections (to be described later in this section), these drifts are characterized by the fact that, on the time scale of our thrust measurements ($\mathcal{O}(1 \text{ minute})$), they can be well described by fitting the stand position data versus time to a straight line. The effect of thermal drifts is accounted for in our data analysis procedure (Sec. 4) and the error in thrust determination due to this effect decreases the longer the linear assumption is valid.

3.2 Tare forces

Tare forces are defined as forces other than the desired thrust that cause a change in the stand position at the time that the thrust measurement is made. The most common example is electromagnetic forces imparted on the stand by the thruster current and

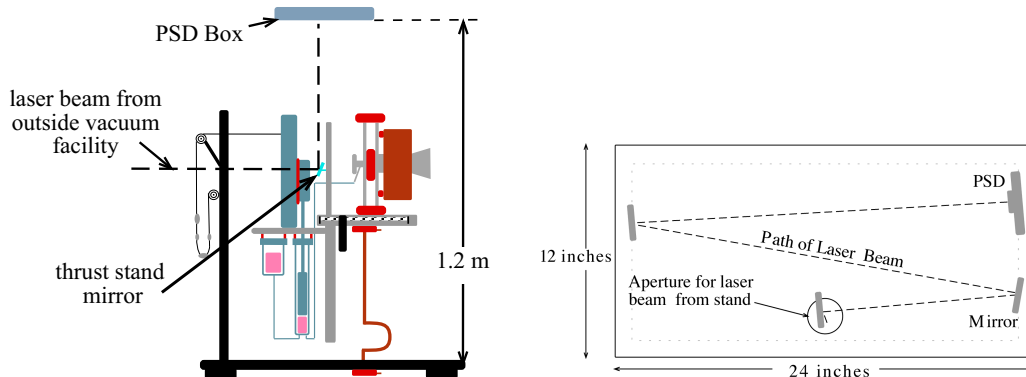


Figure 2: The layout of the components of the laser-based position measurement system. **Left:** The position of the mirror on the thrust stand, laser beam path, and the box containing the sensor and mirrors. **Right:** The top view of the sensor box.

its interaction with thruster subsystems. Necessarily, these forces act on the stand in combination with the thrust. Calibrations, where no thrust is produced, must be performed to determine the magnitude of stand tares. If they cannot be reduced to acceptable levels, they must be characterized and subtracted from the measured thrust to obtain the true thrust.

3.3 Thermal deflections

We define thermal deflections as changes in the stand position as a result of rapid (on the time scale of the thrust measurement, $\mathcal{O}(1 \text{ minute})$) heating or cooling of the flexural elements. When these thermal deflection occur in sync with the thrust measurement (i.e a rapid change in temperature associated with the termination of the thruster current) they can “look” much like a tare force. In our design, these thermal deflections are the most significant source of measurement error, producing stand deflections on par with those produced by the thrust. The most significant cause of thermal deflections appears to be changes in the temperature of the cooling water which is carried to the stand via the flexures. We address thermal deflections in Sec. 5.

4 Thrust Stand Calibration

Calibration is required to determine thrust stand sensitivity and the magnitude of any tare forces. The thruster is shorted during calibration to simulate the thruster current brought to the stand during a firing. The thruster and its subsystems are brought, as close as possible, to their steady-state operating temperatures and the thruster current is set to the desired value. All subsequent events occur at 160 second intervals, chosen for reasons related to thermal drifts and error reduction. The calibration procedure is as follows:

- With the thruster current on, a known force is applied to the stand to measure sensitivity.
- The thruster current is turned off to measure the deflection of the stand due to the tare force.
- A known force is applied to the stand to measure sensitivity.
- The calibration force is removed.
- The procedure is repeated at least five times for each operation point.

A consistent procedure was developed to determine the magnitude of the stand deflection (during calibration or thrust measurement) in the presence of

the thermal drifts in stand position described in Sec. 3. Since the thrust stand demonstrates a linear drift in time over many minutes, we fit a line to the stand position data versus time before and after the force is applied. The fit is done with a minimum of 20 seconds of data. A numerical routine is used to fit the data. Since our last work[3] we have improved the line fit so that it ignores any data where the test of the goodness of the line fit yields a probability of less than 0.8. The number of seconds of data (prior to, or after, the application of the force) used in the fit is increased until the goodness of the fit falls below 0.8 (usually indicating some abnormal disturbance of the stand) or until a maximum of 120 seconds of data is fit. This procedure allows for the best fit to the data to be obtained (largest number of data points included in the fit) while ensuring that we are not trying to fit data where the stand position is being effected by something other than the thermal drift. To summarize, the procedure is as follows:

- The time at which the force is applied is determined (either a sensitivity calibration or thrust force).
- A line fit is performed to the stand position versus time data prior to the application of the force.
- The same procedure is used on the data after the application of the force. In this case however, the fit is begun 20 seconds after the application of the force to allow oscillations in stand position to damp out.
- The deflection of the stand is then determined by taking the difference between the two line fits (before and after the application of the force) evaluated at the time when the force was applied. During calibration this gives the sensitivity of the stand deflection (mV) to the applied force (mN). During thrust measurement the force can be determined from the sensitivity data and the magnitude of the stand deflection.

The stand sensitivity was determined using this calibration and data analysis procedure at various operating conditions (thruster current and applied

magnetic field strengths). A sensitivity of 2.8 ± 0.5 mV/mN (95% confidence) was measured. This sensitivity uncertainty translates to a minimum uncertainty of 17% or a ± 34 mN resolution in measurements of forces, whichever is larger. The spread in the sensitivity data was similar at each condition and no correlations with applied-field strength or thruster current were found. The sensitivity, therefore, does not appear to be effected by thermal loads to the stand. The reason for the large spread in the data was not determined in this work and will be addressed in Sec. 6. The sensitivity and uncertainty are comparable to those we reported last year [3] (Note that the uncertainty reported earlier was the standard deviation not a 95% confidence interval.)

5 Thermal Deflections

The thermal deflection of the thrust stand is the most difficult issue to address when operating steady-state, high-power thrusters. The triple role of the flexures, as the flexural elements, current conductors, and as the chilled-water pipes, is the primary contributor to this problem. In this section we will discuss the evidence for large thermal deflections and our success in reducing their effect on thrust measurements.

5.1 Evidence for Thermal Deflections

A series of calibrations performed with the current conducted on the stand flexures, suggested that the “tare force” we were measuring during calibrations had a large thermal component. The stand required more than 25 seconds to respond to changes in thruster current before resuming its normal thermal drift. In applying a known force, the stand responds immediately and is followed by a damped oscillation, neither of which matched the deflection that occurred during the measurement of the tare force. In addition, the flexure chilled-water temperature over the time of the measurement varied by 2°C (at 500A). Unlike a true tare force which would be expected to be a simple function of thruster current, we have no reason to expect the same to be true for a thermal effect. Due to the uncertainty and difficulty of attempt-

ing to calibrate for such an effect, especially given the very different thermal environment during thruster operation, we decided to reduce thermal deflections of the stand rather than calibrate for them. Also, in our design, the effect of the thermal deflection is to cancel out the stand deflection due to thrust. The thermal deflection is of the same magnitude as the expected thrust (100-500 mN) and acts in the opposite direction. Therefore, during thrust measurements we are measuring displacements of the stand which are near zero, which is not an optimal situation.

5.2 Reduction of Thermal Deflections

In an effort to reduce thermal deflection of the stand, which we determined was largely due to changes in the temperature of the flexures carrying the thrust current, we routed the thruster current through mercury pots. This resulted in the elimination of the chilled-water temperature changes in the flexures. Calibrations performed with the mercury pots showed stand deflections of less than 34 mN (the minimum resolution of the stand). The improvements to stand behavior over the current carrying flexure design are shown in Fig. 3. In this figure we plot stand deflection, in terms of force, versus various calibration currents. The cases for current conducting flexures and mercury pots are shown. Each data point is an average of 5 to 7 trials and error is reported as 95% confidence on the average (the minimum error is 34 mN, from the sensitivity data). The reduction in the thermal deflection of the stand is clear. At a nominal thruster current of 500 A we expect to measure a thrust on the order of 500mN [4]. We see that with the current conducted on the flexures, thermal deflections equivalent to 256 ± 80 mN were observed (51% of the expected thrust). By the use of mercury pots, this deflection was reduced to less 9 ± 36 mN (2% of the expected thrust). Limited by a 17% uncertainty in our stand sensitivity, the remaining effect is within our error bars. Any remaining stand deflections could be either due to additional thermal deflection caused by radiation to parts of the stand other than the flexures or to a true tare force. Further attempts at reducing or calibrating either are not warranted until the sensitivity uncertainty is reduced.

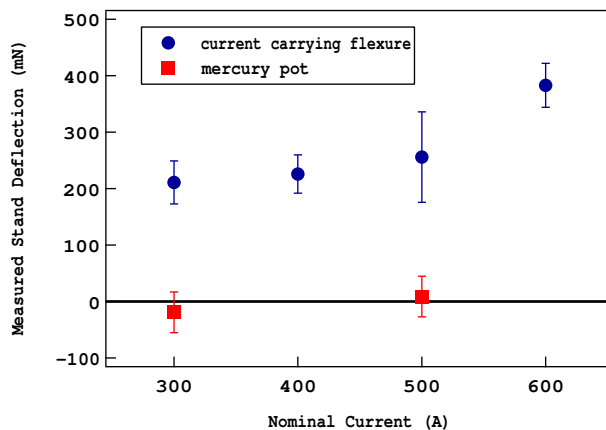


Figure 3: Comparison of stand displacement versus thruster calibration current with current conducted on the flexures and via mercury pots

6 Concluding Remarks

Modifications to our inverted-pendulum thrust stand in which the thruster current was removed from the flexures and conducted via mercury pots are shown to reduce thermal deflection of the stand to within our measurement resolution ($\pm 17\%$). This eliminates the largest source of error in thrust measurements in our stand design. Determinations of tare forces with the reduced thermal deflection, show that the actual tare force is small compared to the thermal deflection and zero with our present resolution. Thermal drifts in the stand position are accounted for in the data analysis routine and are not significant sources of error.

While significant improvements in thrust stand behavior were achieved by reducing thermal deflections, there are still issues which need to be addressed. Water cooling was removed from the current conducting elements on the stand to achieve more uniform flexure temperature. This resulted in high conductor temperature (up to 100°C) which could cause smaller thermal deflections by heating various parts of the stand. Additional radiation to the stand from the thruster during operation may also be an issue, this has yet to be determined.

The most critical issue to be addressed in the operation of the thrust stand is the spread in the sen-

sitivity data (Sec. 4). The precision of our thrust data is limited by the 17% uncertainty in our stand sensitivity. The most probable source of this uncertainty is the large number of thermocouple and signal wires which must be brought to the stand. Small stand deflections, typically less than 0.1 mm, during thrust measurement, make the elimination of all impediments to free stand motion critical. Now that the mercury pots have reduced thermal deflections, the repeatability issue can be more carefully addressed.

and JPL to NASA-JPL (Items 8 and 9 of Delivery Schedule). Technical report, RIAME, MAI, Moscow, Russia, December 1998.

7 Acknowledgements

LiLFA research at EPPDyL is funded by NASA/JPL's Advanced Propulsion Group, the NASA Graduate Student Research Program (GSRP) and the DOE's Plasma Science and Technology Program at Princeton University. We would also like to thank Bob Sorenson for his expert technical support of this research.

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