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Technical Notes

Method for Measuring the Applied-Field Thrust Component of Plasma Thrusters

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I. Introduction

THE thrust generated by plasma thrusters typically consists of several components, such as gasdynamic, self-field, and applied-field thrust components. Thrust stands generally measure the sum of such components. There is often a need to make an isolated measurement of a component: for instance, when a theoretical model of a certain thrust component requires experimental verification.

One thruster that can benefit from isolated-component thrust measurements is the applied-field Lorentz force accelerator (AF-LFA), for which various models of its applied-field thrust component have been proposed [1–7]. However, applied-field component thrust stands in the literature are limited to low-current (≤ 6 A) solenoids [8], and they are poorly suited to the high currents typical of AF-LFAs, which require cooling and a means of calibrating for electromagnetic tare forces. In this Note, we present a method for directly measuring the applied-field thrust component for high-power thrusters, and we apply it to the case of a 30 kW steady-state AF-LFA.

II. Thrust Stand Method and Design

A. Method

To directly measure the applied-field thrust component, we constructed an inverted pendulum thrust stand, which is similar to that used to measure the total thrust on a high-power Lorentz force accelerator described by Haag in Ref. [9]. The difference is that the flexures support only the solenoid (illustrated in Fig. 1), which can move independently of the thruster, which is fixed to the laboratory reference frame. Because the applied-field component of the thrust exerts an equal and opposite force on the solenoid, a calibrated measurement of the deflection of this inverted pendulum is a direct measurement of the applied-field thrust component.

The force exerted on the solenoid is augmented by electromagnetic tare forces from azimuthal currents to the thruster electrodes in proximity to the solenoid. We considered two methods to account for this tare force. The first method consists of making a measurement for a given set of operating parameters and then repeating that measurement with the solenoid current running in the opposite direction. The force from the applied-field thrust will be the same in each instance, but the tare force will be in opposite directions. The average of the two measurements is then equal to the applied-field thrust component.

In the second method, the measurement is repeated with the thruster electrodes physically shorted. This measurement provides the tare force, which can then be subtracted from the measurement made while firing. This method requires that the short does not contribute to, or subtract from, the preexisting azimuthal currents, which means it must be strictly radial and within the thruster volume. We tested each method and present the results in Sec. III.

The applied-field thrust component is dependent on the shape and strength of the magnetic field within the anode, and so care must be taken to ensure that the motion of the solenoid does not significantly alter either of these parameters. For all measurements in the presented work, the magnetic-field strength at the exit is within 0.22 deg of the thruster-off value, and the angle of the solenoid is within 0.03 deg of the thruster-off value. Because the applied-field thrust is approximately proportional to the applied-field strength, these small deviations can be neglected.

B. Thrust Stand Design for a Thirty-Kilowatt Applied-Field Lorentz Force Accelerator

The operation of the solenoid for the 30 kW AF-LFA requires 350 A and active cooling. To accommodate these requirements without impeding the motion of the thrust stand, copper pipes (0.375 in. outer diameter, and 0.245 in. inner diameter) are used as the flexures, which carry all necessary current and cooling. The dimensions of the flexures are based on the design criteria outlined in Ref. [9], the dimensions of our vacuum facility, and the sensitivity of our linear variable differential transformer (LVDT). Because the temperature and spring constant of the flexures are functions of current through the solenoid, an open-cycle cooling system was implemented and found to reach a steady-state operating temperature in under 2 min for any current level in our operational range of up to 350 A. No change in flexure temperature was observed while firing the thruster. Electromagnetic tare forces between the flexures and the components carrying current to the thruster electrodes were minimized by separating the two as much as possible within the constraints of the vacuum tank dimensions.

C. Measurement Procedure

To correlate deflection with force, we measure the deflection of the thrust stand using a Macro Sensors PR 750-100 LVDT, which has a sensitivity of 155 mV/V/mm. After the solenoid coolant reaches steady state, we fire the thruster and record the voltage from the LVDT. Then, the thruster current supply is turned off, but the solenoid is left on at a constant current. This ensures that the temperature of the flexures and the magnetic forces on nearby metallic surfaces remain constant. A second voltage is recorded. The difference in voltage between the two measurements represents the distance the thrust stand is deflected.

To calibrate the deflection measurement, a known force is applied to the pendulum. For forces under a few newtons, the change in voltage measured as a result of deflection of the thrust stand is found to be linear with force. Therefore, application of a single known force, in addition to the calibration-off measurement, is sufficient to calibrate a voltage measurement. However, the measurement is repeated at a number of force levels after each deflection measurement to ensure the linearity of the response.

We apply a known force by means of an actuator and a scale, as is schematically illustrated in Fig. 1. The scale translates a mass back and forth through remote control. A cable is strung from the end of the scale over a pulley and attached to the back end of the thrust stand along the thruster axis. As the mass moves further from the pivot point, the scale applies a greater calibration force to the thrust stand.

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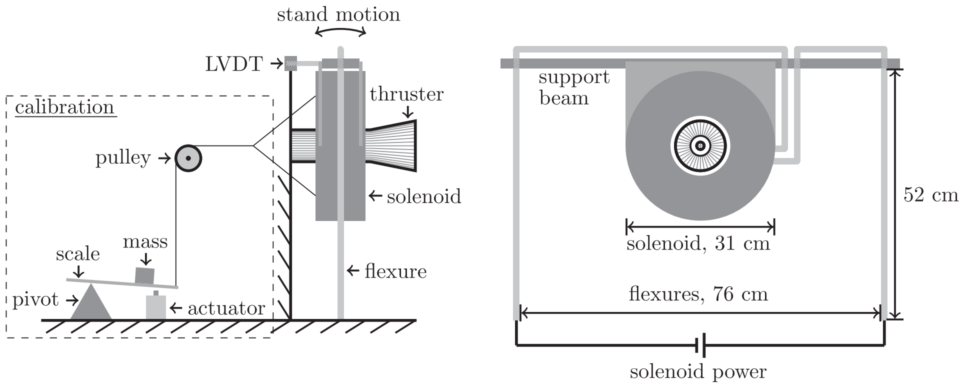
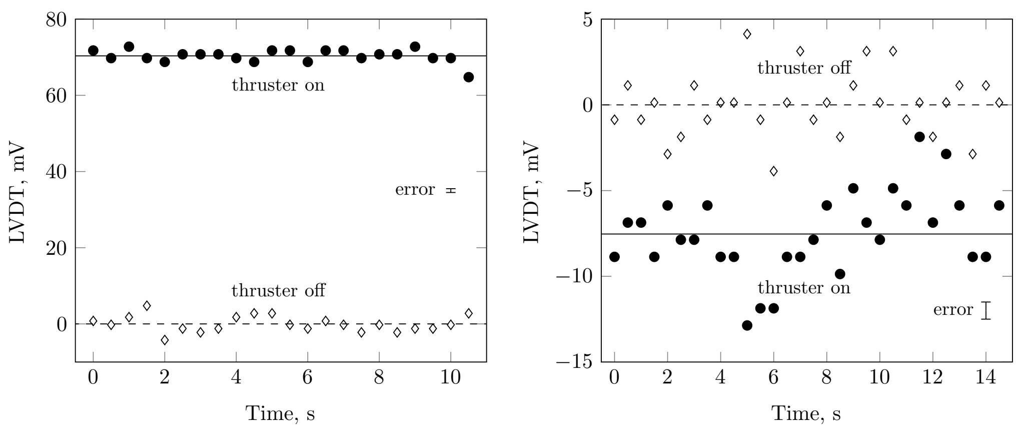


Fig. 1 Applied-field solenoid supported by an inverted pendulum that is free to move with respect to the thruster, which is fixed in the laboratory frame.



a) Parallel deflection measurement **b) Antiparallel deflection measurement**

Fig. 2 Deflection of the thrust stand as measured by an LVDT with the electromagnetic tare force a) parallel to the thrust and b) antiparallel to the thrust.

Force is determined as a function of mass position by calibration with a series of seven hanging weights up to 1.2 N. For these same weights, the LVDT output is found to be linear with force, with $R^2 = 0.9996$.

III. Experimental Results

We fired the AF-LFA at 400 A at steady state, with an applied-field strength of 0.056 T and a lithium mass flow rate of 8 mg/s. Background pressure was maintained under 5×10^{-5} torr. We made two measurements for the same operating parameters, as is shown in Fig. 2. First, we measured the total deflection of the stand with the electromagnetic tare force parallel to the thrust. We then reversed the current direction through the solenoid and took a second measurement. Each deflection measurement consisted of the average LVDT output taken over a 10–15 s interval.

We calibrated the thrust stand with its flexures at the operating temperature and measured a sensitivity of 3.4 mN/mV. Averaging the deflection measurements from each solenoid configuration yielded an applied-field thrust of 108 ± 14 mN. We shorted the thruster and we measured an electromagnetic tare force of 137 ± 17 mN that, subtracted from the parallel force measurement, yields an applied-field thrust of 106 ± 19 mN. Adding the same tare force to the anti-parallel force measurement yields an applied-field thrust value of 111 ± 20 mN. The magnitude of the tare force, which was larger than the thrust, indicates that there was a significant azimuthal current path to the thruster near the solenoid. All results are summarized in Table 1.

Table 1 Results of each thrust measurement method

Method	Measurement, mN	Error, mN
Alternating *B* field	108	±14
Parallel tare	106	±19
Antiparallel tare	111	±20

Our three thrust measurements for the same operating conditions are in agreement. In addition, all three methods provide applied-field thrust component values that are less than the total thrust (224 mN) measured with equivalent operating conditions [10] and within the range of values predicted by the model of Tikhonov et al. [11] for applied-field thrust (99–197 mN). We recommend future experimental campaigns employ the first method used, in which the solenoid is run in both directions and the measurements from each configuration are averaged. This method is preferred because measurements can be made during a single operating period without venting the vacuum tank. In addition, we avoid inadvertently adding to or subtracting from the existing azimuthal currents to the thruster electrodes through an artificial electrical short that may not be strictly radial. This method also avoids damage due to high temperatures resulting from large currents through an electrical short in the thruster volume.

The 13% error in our thrust measurement is due to the variability in position, which does not scale with the magnitude of the measurements made. Consequently, we anticipate smaller relative errors in a higher-thrust regime.

IV. Conclusions

A method was presented for directly measuring the applied-field component of the thrust generated by a plasma thruster, which consisted of fixing the thruster to the laboratory frame and supporting the solenoid separately on a thrust stand. This method was demonstrated on a Lorentz force accelerator, and it was found that electromagnetic tare forces were the primary source of error in the initial measurement. These tare forces were accounted for by averaging the measurements with the applied magnetic field in opposite directions.

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