Colloid Microthruster Test Stand

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A single-axis simulator was developed for testing a colloid microthruster while measuring its thrust directly over the range from 1 to 10 μlb at ± 0.5 μlb accuracy. This test stand duplicated actual spacecraft interfaces, utilizing battery input power, command circuits, and telemetry. It was used to evaluate microthruster performance and for correlating indirect time-of-flight thrust data. Measurements were taken at load-to-precision ratios greater than 8 × 10^7 lbm/lbf.

I. Introduction

A TEST stand for colloid thrusters[1] was designed, fabricated, and evaluated for measuring system thrust directly at levels ranging from 1 to 10 μlb. This test stand simulated actual flight conditions, including vacuum environment, battery input power, remote command circuits, and telemetry. The high load-to-precision ratio (> 8 × 10^7 lbm/lbf) required for thrust measurement to 0.5 μlb resolution imposed additional sensitivity constraints on test stand design, which led to a new method for suspension fabrication. This test stand provided the means for correlating indirect thrust measurement techniques with direct thrust data.[2]

Direct transverse thrust measurements of an electrostatically deflected colloid beam have been performed by suspending only the deflection electrodes from an electrobalance.[3] To measure full thrust (rather than just the transverse thrust component), the entire thruster weight must be supported. Additionally, electrical and propellant feed connections to the thruster must not adversely compromise supporting suspension sensitivity.

Indirect thrust measurements have been made by observing the deflections resulting from colloid thruster exhaust impingement on a target collector.[4] These measurements are based on several assumptions, which, however, neglect particle evaporation and collision within the test chamber.

The sources of error frequently encountered during direct low-thrust measurement are listed in Ref. 5. A comparison of several vertical axis, flexure pivot microthrust stands developed for direct thrust measurement from 1 μlb to 10 mlb is given in Ref. 6. As pointed out in both references, this method of suspension is extremely sensitive to tilting effects, which may be produced by small temperature differences during operation. Nevertheless, an accuracy of ±5% at 1 μlb is specified for one version of this test stand, which has a load carrying capability of 20 lb.

A single-axis space simulator basically consisting of a servo-driven support cable and platform[7] led to the development of a microthruster test stand for measurements from 10 to 200 μlb.[8] Servo techniques afford two advantages when compared with a purely mechanical torsion balance. First, the effective spring constant of the balance system may be greatly increased to obtain relatively fast response for the low-level thrust measurement. Secondly, servo techniques permit introduction of artificial balance damping. Test results with this thrust stand at 10 μlb indicated 6% accuracy. The stand itself was designed to support 100 lb.

II. Test Stand Description

The single-axis test stand schematically depicted in Fig. 1 provides full-scale colloid microthruster system testing. It is basically a torsion balance, consisting of a 5-ft aluminum I-beam platform suspended from a 3-wire beryllium copper suspension. The microthruster is placed near one end of the balance and thrusts in such a manner as to twist the suspension about its vertical axis. Batteries and telemetry are suitably mounted to help counterbalance the thruster.

A direct reading light beam system indicates the angular rotation of the test stand without producing forces on the balance and in a manner insensitive to translational vibrations and noise. An image of a fine wire, after reflecting off the balance mirror, is focused on a scale outside the vacuum test chamber. Thrust lever and optical lever arms are such that 1 μlb thrust yields about 0.16-in. deflection on the optical readout scale.

Some operational features of this test stand include a vacuum feedthrough at the top of the test chamber, which allows the stand to be raised off or lowered onto its stops, and to adjust the zero balance position. One stop is electrically insulated from the test chamber, permitting operation from external power supplies when thrust measurements are not being performed. In addition, the battery may be charged to full capacity between discharges without disturbing the vacuum test chamber environment.

Balance oscillations are damped by using electromagnets to induce eddy currents in damping vanes attached to the beam. Magnets on opposite sides tend to reduce induced vibration torque and cancel magnetic effects that might result when magnet current is varied. All balance parts are fabricated from nonmagnetic materials.

All electrical and propellant feed connections to the thruster are made on the test stand platform so that they do not directly contribute to suspension compliance. Power for the thruster system as well as for command and telemetry systems is supplied from sealed batteries. The command channels comprise light-beam triggered circuits that operate latching reed relays. Twenty command operations are possible, including separate control of thruster subsystems and adjustment of thrust level in eight steps. Data on thruster operation, battery status, and platform temperature are commutated onto a 70 kHz pulse-amplitude-modulation (PAM)/FM signal and are transmitted through a small vacuum gap coupling capacitor to a subcarrier discriminator. The result-

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ing signal is either recorded on a galvanometer recorder or monitored with a digital frequency counter. PAM formating is flexible, allowing up to 15 channels of data to be transmitted.

Figure 2 shows the actual test stand prior to installation in a 4-ft × 8-ft vacuum chamber. The colloid microthruster system, shown at the left in this photograph, consists of two thrusters (which may be operated independently), propellant, feed system, and a power and signal conditioning unit. Telemetry batteries occupy the space originally intended for telemetry circuits while the microthruster battery is suspended from the balance beam between the suspension and one support. This arrangement improves static balance and makes the space under the center of the beam available for signal coupling capacitors. The command and spacecraft power simulator circuits are "breadboard" packages placed along the upper beam surface. The telemetry commutator and voltage controlled oscillator are mounted underneath the beam near the suspension.

The table that supports the beam when at rest also provides damping magnet mounting. This table is fastened to the interior of the vacuum chamber as follows. Two aluminum hoops are expanded tightly within the tank circumference using expander screws. Structural members made from aluminum angle stock are then bolted to these hoops without damage to interior tank surfaces. Finally, the table is bolted to horizontally aligned aluminum angle pieces.

A special high-voltage feedthrough on the vacuum chamber is used to suddenly short the thruster to ground through a thyratron circuit in order to provide the instantaneous beam turnoff that is needed for time-of-flight measurement.[3] In this manner, indirect time-of-flight measurements were correlated with direct thrust stand data.

Suspension

Limitations on torsion balance sensitivity are frequently encountered at high load-to-precision ratios. One solution to this problem is to divide the supporting wire into a large number of small filaments. This reduces the shear stresses without changing the tension stress so that much lower torsional forces are required to produce a given deflection. In principle, the torsional forces in the filaments can be reduced to zero in the limit, but a second torque arising from the lifting effect of twisting the filament bundle places a lower limit on the spring constant of the torsion balance. The lifting torque contribution is dependent on both the magnitude of the load and on the location of its center of gravity relative to the suspension.

A better understanding of this important point can be gained by referring to Fig. 3. A weight W, the center of gravity of which can be shifted, is suspended by round wires of radius r, length L, and torsional modulus G. When the center of gravity is at A, the torsional restoring coefficient due to the torque in N wires is $N(\pi R^4 G/2L)$. An additional restoring force, due to the tension in the supports, and their separation $2S$, increases the restoring coefficient by WS^2/L. This contribution is dependent on the weight supported and varies with the position of the center or gravity. When the center of gravity is under B, directly under one wire, the restoring constant is due only to the wires and is independent of loading.

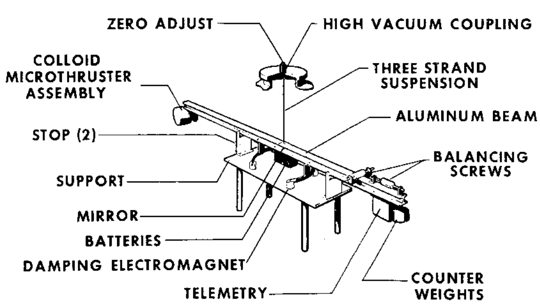

Fig. 1 Single-axis microthruster test stand schematic.

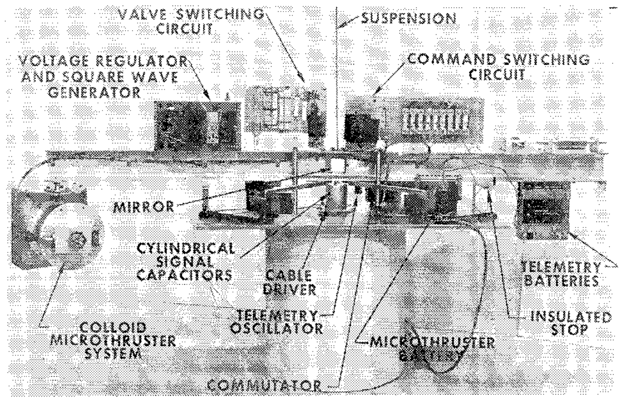

Fig. 2 Colloid microthruster test stand prior to installation in vacuum chamber.

The right wire has no tension but does contribute to the torsional restoring force. When the center of gravity moves toward C, the restoring force reduces further until the right column, now under compression, can buckle and snap the system away from its normal equilibrium.

This system can be used to increase the sensitivity by loading the compression fiber to its critical load. This method in essence matches two large forces of opposite sign to produce a very small difference term that is extremely sensitive to small changes in the position of the center of gravity of the system relative to the supports. There are many versions of this approach, e.g., the critically loaded column, or the beam balance with its center of gravity almost on the pivot axis; all suffer from sensitivity to minor mass shifts produced by thermal bending or propellant consumption. Attempts to eliminate this fault through well-balanced servo systems have been uniformly troublesome and unsatisfactory.

A major feature of this test stand is that center of gravity shifts or load changes do not cause major changes in operation. This is accomplished by 1) minimizing suspension wire separation distances to decrease loading effects, 2) keeping the center of gravity low so that it can move under the center of the support without altering the tension in the individual strands of the suspension, and 3) making the suspension sufficiently stiff that loading effects are minimized (at some loss of sensitivity).

The suspension selected for this purpose uses three 0.020-in.-diam beryllium copper wires equally spaced on a 0.040-in.-diam circle. The total suspended weight during thrust measurement is 41 lb, which stresses these wires to 43,500 psi. The wire procured for this suspension is furnished in $\frac{3}{4}$ H temper, which provides a yield point between 90,000 and 112,000 psi. Subsequent precipitation hardening further improves mechanical properties. The suspension torsional restoring constant is calculated to be 14.5 mlb-in./rad. The sensitivity effect due to loading is 0.7 mlb-in./rad.

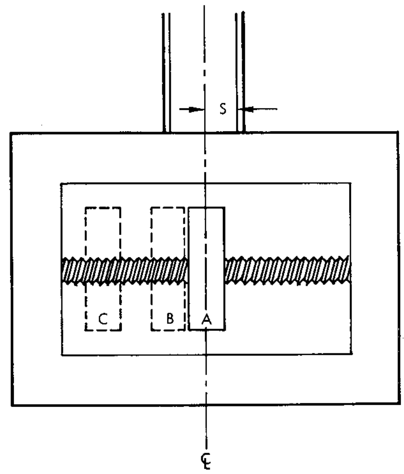

Fig. 3 Center of gravity shift changes torsional stiffness.

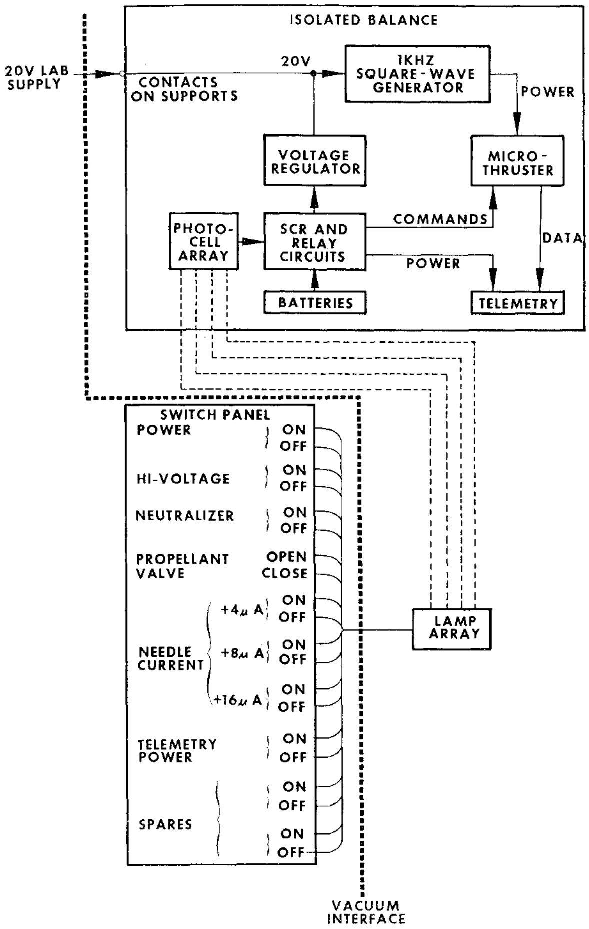

Fig. 4 Thrust stand command circuits.

A novel method was developed for assembling the torsion balance suspension wires without affecting their fully developed mechanical properties (after heat treatment). This is accomplished by potting them with epoxy adhesive in hollow, threaded end pieces. The epoxy to suspension wire interface bond is subjected to very low shear stresses, thereby enabling the suspension to support relatively heavy loads without encountering creep deflections during operation.

The balance suspension was fabricated by first removing the silver coating from the wire surfaces in an 180°F solution of HNO_3 and H_2SO_4. The wires were then attached to a straightening fixture and heat treated at 600°F for $1\frac{1}{2}$ hr. The oxide scale on the wires was removed by dipping them in a bright dip. They were then nickel plated, resulting in a 0.0196-in.-wire diameter after plating. One end of the wires was potted into a hollow threaded end piece with Epon† 934 adhesive and cured at 180°F for 2 hr. The other ends were then dead weighted and similarly bonded into their threaded end piece.

This suspension assembly was creep tested for 11 days under 40 lb dead weight load. Measurements were taken to determine whether the wires would creep at the epoxy bond line. No creep deflections were observed using an instrument capable of measuring 0.0005-in. deflection.

Command and Telemetry Links

Electrical operation of the thrust measuring system may be described with reference to the diagrams shown in Figs. 4 and 5. (See Ref. 3 for a description of the thruster circuit.) The list of commands which are implemented for thrust balance operation are labeled on a switch panel exterior to the vacuum chamber. Each switch is a double-pole, momentary contact push button which turns on a pair of lamps in a three by three lamp array. On the thrust balance a photoconductive cell connected to the gate of a low-current silicon controlled rectifier (SCR) is aligned with each lamp. Four SCR's connect bus bars to a positive voltage, and five of them connect lines to a negative return. Actuating coils of either single- or double-coil reed relays are connected through diodes and series capacitors to the SCR lines so that the nine-lamp array operating in pairs can control a 4×5 matrix of 20 switch coils. The double-coil relays are of the magnetic latching type; the series capacitors allow the SCR's to turn off later each actuation. Accordingly, on and off operations for the same circuit are considered as two commands. Each needle current on operation adds the indicated amount of current on the switch panel. Minimum current with all three switches off is 4 μa; maximum with all three on is 32 μa. Power for the SCR circuit is provided continually while the test assembly is under vacuum; the command circuit is able to switch power to the telemetry and thruster circuits as required.

The thruster battery's voltage and discharge characteristic requires that a voltage regulator be used between it and the input to the 1-kHz square-wave generator in order to ensure that the potential at this point is a constant 20 v. When the thrust balance is resting on its supports, the microthruster can be operated from a 20-v laboratory supply through contacts on the supports, so that battery charge may be conserved. As shown in Fig. 4, the SCR relay contacts control microthruster operation, and telemetry signals are directly input to the thrust balance telemetry circuits.

Early tests required the valve coil and command circuit to operate at needle voltage. Accordingly, a special SCR-relay circuit, shown in Fig. 2, was built for this valve. This board includes its own battery that operates both the SCR circuits and the valve coils. These high-voltage circuits and lead wires going to the valve were carefully shielded to prevent electrostatic forces from affecting thrust measurements.

Figure 5 shows more detail of the means used to handle the telemetry signals. Six information channels are read from the microthruster power and signal conditioning unit. In addition, zero and full-scale (0.250 v) signals are made available, as well as a voltage proportional to that at the terminals of the thruster battery. These signals are connected through a patch board to 15 pins of a PAM commutator, so that the six data channels are sampled twice and the other three channels

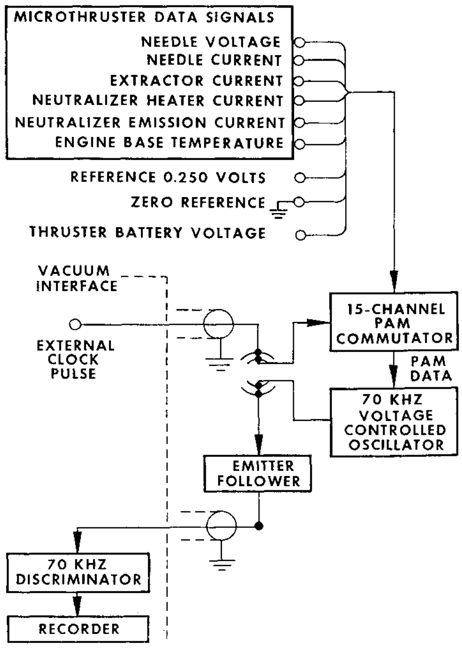

Fig. 5 Telemetry data channel.

† Trademark, Shell Chemical Company.

once in each "frame." The output modulates the frequency of a voltage controlled oscillator (VCO) at a nominal frequency of 70 kHz. The VCO output is adequate to drive a 70 kHz discriminator through a coupling capacitance of only a few picofarads, and is taken from the thrust balance through one of two cylindrical capacitors shown in Fig. 2. The stator segments of these capacitors are support table mounted, and are connected through vacuum feedthroughs to laboratory instruments. A low-level emitter follower is used in the 70-kHz line to drive the capacitance of about 20 ft of coaxial cable which leads to the discriminator. The discriminator output reproduces commutated information fed to the VCO with an over-all gain of four, so that for thruster signals in the range from 0 to +0.25 v, the strip-chart recorder sees 0 to 1 v signals. An externally generated clock pulse is coupled to the thrust balance through the other cylindrical capacitor for stepping the commutator from one pin to the next so that this rate may be adjusted to any convenient value during runs. The commutator may also be stopped on any one pin in order to make either analog recordings of a given channel or to make digital frequency measurements of VCO output.

It may be noted that the unconventional use of a coupling capacitor and simple emitter follower between the VCO and discriminator has saved the added power, complexity, and expense of a telemetry transmitter and receiver. Likewise, the use of a slow stepping rate (on the order of 1 step per second) allows strip-chart recording of the discriminator output. Identity of each channel is readily recognizable by its sequential position with respect to full-scale and zero reference channels. This results in saving the cost and complexity of a decommutator and sample-hold circuits.

III. Calibration and Error Analysis

The torsional restoring constant for the suspension was determined by substituting a calibrating beam of known moment of inertia for the test stand platform, and by measuring the natural frequency of oscillation for this system. The torsional restoring constant actually measured 12.3 mlb-in./rad, somewhat more sensitive than the design value. Calibrations performed approximately four months apart differed less than 0.2% in measuring the period of oscillation.

Table 1 sums up the maximum estimated errors in the thrust balance measurement. As can be seen from this table, uncertainties in determining both the thrust equilibrium point and the balance zero point must be taken into account. The error connected with nonrotational oscillation modes is due to the fact that small amplitude short period nonrotational oscillations are superimposed on the main $6\frac{1}{2}$ min period rotational oscillation mode. The equilibrium point both in the thrust position and the zero position is determined by first magentically dampening the balance to rest, and then removing the damping to measure the midpoint of the resultant small amplitude oscillations. The uncertainty in the midpoint due to these nonrotational oscillations is reflected in Table 1. The next two items in Table 1 reflect a conservative upper limit to the accuracy of the length measurements. The uncertainty due to thrust vector misalignment is a purely geometric effect producing a 2% uncertainty in the actual length of the thrust lever arm. Finally, it is believed that the measurement of the balance calibration constant is accurate to within ±1%. The maximum error based on these quantities is estimated to be ±0.4 μlb ± 5%.

Table 1 Thrust measurement error estimates

Reading errors	
Zero point (±0.5 mm)	0.1 μlb
Thrust point (±0.5 mm)	0.1 μlb
Nonrotational oscillation modes	
Zero point (±0.5 mm)	0.1 μlb
Thrust point (±0.5 mm)	0.1 μlb
Optical lever arm	1%
Thrust lever arm	1%
Thrust alignment (±5°)	2%
Calibration constant	1%

IV. Conclusion

The first direct measurement of colloid microthruster system thrust was taken on April 5, 1968. Since that time, the test stand has been used repeatedly for evaluating system performance and for correlating indirect time-of-flight thrust data. Numerous measurements have been made from 1 to 8 μlb and an unusual operating point led to a measurement at 18 μlb.

This test stand is an excellent single-axis simulator for testing a colloid microthruster system. Besides providing the means for direct thrust determination, all spacecraft interfaces are utilized during test, and all operational environments may be simulated by suitable test chamber selection.

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