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PRELIMINARY TESTS OF A SINGLE-AXIS AMMONIA-RESISTOJET ATTITUDE CONTROL SYSTEM

by Harold Ferguson, James S. Sovey, and Henry R. Hunczak

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1968

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ABSTRACT

Performance data are presented for an ammonia-resistojet attitude control system designed for use with stable platform type satellites in the 225- to 450-kg class. The system includes the fast-heatup thrusters (2 mN thrust), propellant storage and feed components, control logic, and power and signal conditioning. The ability of the system to acquire and maintain a soft limit cycle control mode within an attitude accuracy of $\pm 0.2^{\circ}$ was demonstrated. In particular, thruster performance was obtained which indicated that increased preheat time and pulse width cause significant decreases in propellant mass flow rate and thrust and an increase in specific impulse.

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SUMMARY

Performance data are presented for an ammonia-resistojet attitude control system designed for use with stable platform type satellites in the 225- to 450-kilogram class. The system includes the fast-heatup thrusters (2 mN thrust), propellant storage and feed components, control logic, and power and signal conditioning. The single-axis tests were conducted in May, 1965 using a gas-bearing facility operating in a vacuum.

The ability of the system to acquire and maintain a soft-limit-cycle control mode within a specified attitude accuracy of $\pm 0.2^{\circ}$ was demonstrated. In particular, thruster performance was obtained which indicated that increased preheat time and pulse width cause significant decreases in propellant mass flow rate and thrust and an increase in specific impulse.

INTRODUCTION

The requirements for attitude control of a stable platform type satellite have resulted in the generation of several control techniques and thruster system concepts to perform these functions. These techniques almost universally require thrust in the millinewton range. A number of thruster types have been developed (e.g., cold gas, electrothermal, and electromagnetic) in an attempt to meet these needs.

With the development of thrusters in the millinewton thrust range, considerable effort has been expended on the measurement of thruster performance in an attempt to determine the adaptability of real thrusters to the control functions and to predict weight and power requirements for long-term missions. For low-thrust electrothermal thrusters, the problem is further compounded by the variation of performance with several system parameters (e.g., thruster warmup time, pulse width, etc.). Thus, the actual impulse delivered to a spacecraft from a millinewton electrothermal thruster system can most accurately be determined by observing the control maneuvers of a real system in an experiment which simulates the desired operational environment.

The present investigation was conducted in May, 1965 to determine the performance of a nominal 2-millinewton resistojet thruster system (developed under NASA contract, ref. 1). Ammonia was used as the propellant in conjunction with a control technique proposed by Vaeth (ref. 2). Results are presented for acquisition and control in a soft limit cycle mode and for thruster performance.

APPARATUS AND PROCEDURE

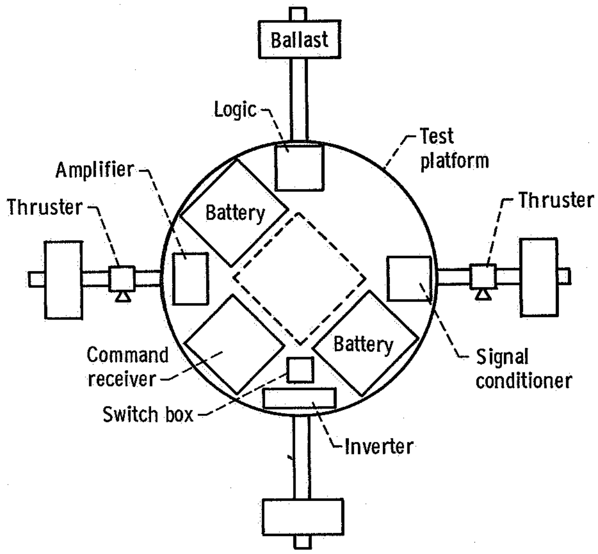
The experimental apparatus consists of two thrusters, the propellant storage and feed module, power and signal conditioning, light source and sensor, and control logic. This system was mounted on a platform which was suspended from a gas bearing mounted from an overhead support in the Lewis Research Center 4.6- by 18.3-meter vacuum facility. This arrangement permitted control about the vertical axis and allowed the impulse delivered by the system to be measured. The platform also contained a battery power supply, a commutator, relays, and a telemetering transmitter. The entire package was operated remotely from a control center.

The assembly of the complete system is shown schematically in figures 1(a) and (b). The propellant supply module is located at the center and below the platform. Thrusters are mounted 0.61 meter from the geometric center of the plate. The sensor is located at the edge of and below the plate 0.46 meter from center. The separation of light source and sensor is 0.61 meter. Four weights mounted in tracks were used for static balance and to obtain the desired moment of inertia.

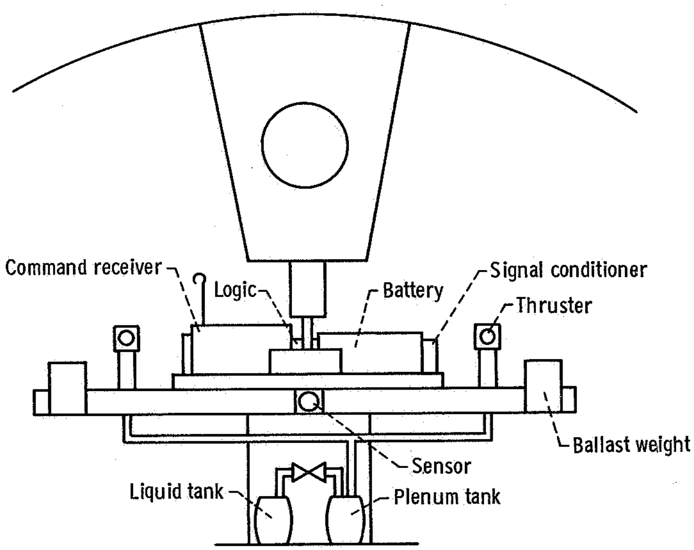
Thruster System

A complete description of the design and fabrication of the system is given in reference 1. The present discussion is limited to functional and qualitative aspects of the components, their operation, and the measurements and procedures employed in testing. The schematic assembly of the thrusters and propellant supply is shown in figure 2.

Thruster. - The configuration of the thrusters together with the pressure transducer used in these tests is shown in figure 3. Each consists essentially of a molybdenum heater tube and nozzle through which the ammonia propellant flows while being heated by contact with the inner wall. Pertinent dimensions are given in the figure. The thrusters were designed to operate at pressures to two atmospheres and input



(a) Top view.



(b) Side view.

Figure 1. - Schematic diagram of system assembly.

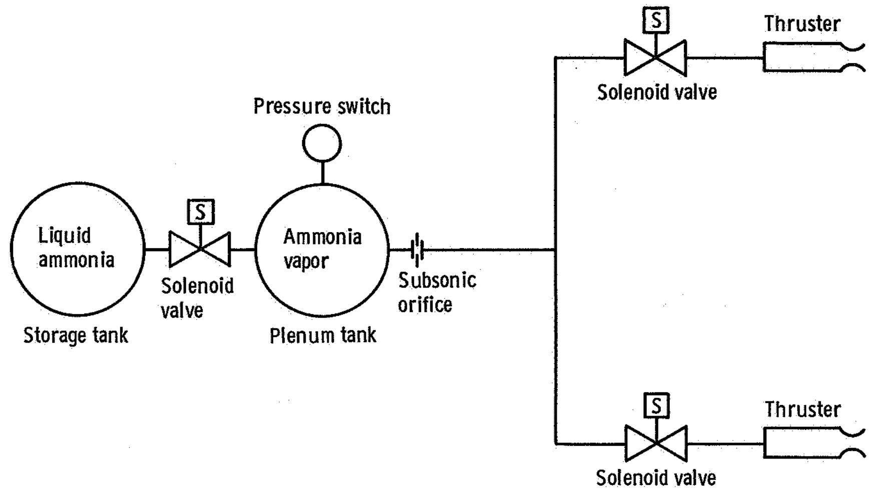


Figure 2. - Propellant storage and feed system.

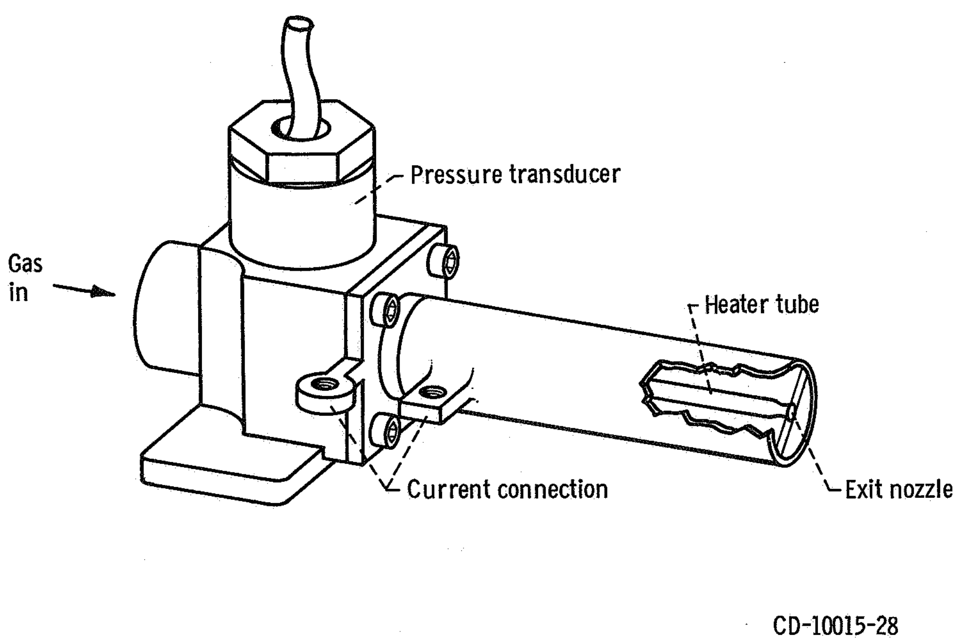


Figure 3. - Thruster assembly. Nozzle nominal throat diameter, 0.18 millimeter; nozzle nominal exit diameter, 0.76 millimeter.

powers to 40 watts with ammonia as the propellant. The nominal design conditions were an operating pressure of 9.4 newtons per square centimeter, a power input of 15 watts, and a thrust of 2 millinewtons at a specific impulse of 120 seconds. The flow valve was mounted close to each thruster assembly. Two thrusters were used for attitude control about the vertical axis, one for clockwise and the other for counterclockwise rotation.

Propellant storage and feed. - The storage and feed system consists of a liquid-ammonia-supply tank and a plenum tank in which the propellant is held in the vapor state at a pressure controlled by a pressure switch operating in conjunction with a solenoid valve. The pressure switch was designed to limit the upper and lower pressure levels in the plenum, thereby controlling the pressure at the thruster heater tube inlet. In the system tested the liquid-supply tank was sized for laboratory tests only and had a storage capacity of approximately 0.5 kilogram of ammonia. The plenum tank volume (which influences the valve cycling rate) was approximately 775 milliliters. The flow rate was measured with a 0.25-millimeter-diameter subsonic orifice immediately downstream of the plenum tank. A single supply tank and plenum provided propellant for both thrusters.

Power and signal conditioning. - Power for the system was provided by a battery pack with a capacity of 60 ampere-hours at 24 volts dc. Three voltage converters were provided to convert the 24 volts dc to plus and minus 28 volts dc, and this output was used for the system components. All valves operated at 28 volts and thus required no additional power conditioning. Power conditioning was required for the pressure transducers, the signal conditioning equipment, and the thruster heaters. For the thruster heaters the dc input was converted to 10 000 hertz ac and was reduced with transformers to the lower voltage required by the heaters. The power conditioning is illustrated schematically in figure 4. Signal conditioning was provided to convert the output of the instrumentation to the 0 to 5 volts required for telemetry encoding.

Light source and sensor. - A functional diagram of the position sensor and light

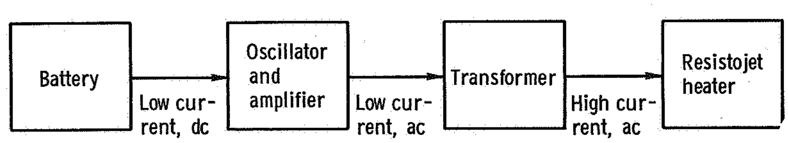


Figure 4. - Schematic diagram of resistojet power conditioning circuit.

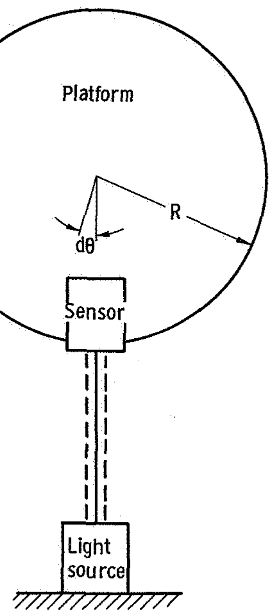


Figure 5. - Functional diagram of light source and sensor.

source is given in figure 5. The equipment was designed only to facilitate testing. The sensor consists of two adjacent photoresistive elements which are differentially illuminated by the amount of incident light impinging on the surface. Incident light was derived from a light source which used an appropriate lens system to produce a collimated beam as shown. The difference in output of the two cells is a measure of the angular displacement of the platform.

Control logic. - A diagram of the essential features of the control logic is shown in figure 6 and represents a typical "proportional plus derivative of error" control method. The output of the sensor was fed into an amplifier and subsequently into the lead network. The lead network generated a control function which was proportional to the sum of the displacement θ and the rate of change of displacement $\dot{\theta}$. This signal was then fed into the switching circuit which used a polarity detector to determine operation of the appropriate thruster.

The control method is one proposed by Vaeth (ref. 2) which uses two sets of commands, one for a fixed pulse of short duration and another for larger error which demands continuous thrusting until a preset limit of the control function is attained.

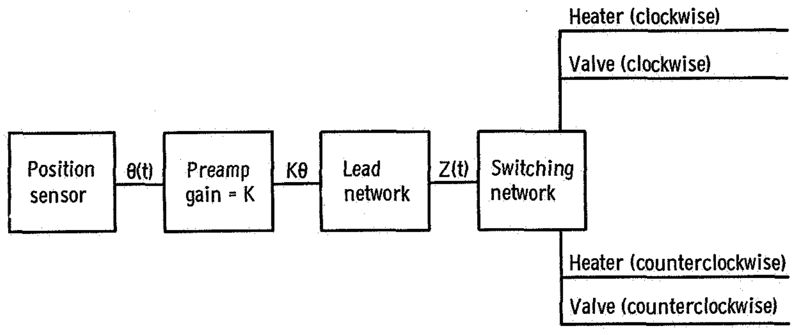


Figure 6. - Control logic diagram.

Test Procedure

Each test was initiated by giving the platform some initial displacement and rate by command. The system was then switched to automatic control and allowed to acquire the desired position and to undergo several pulses. The turbining torque of the gas-bearing support system resulted in a unidirectional disturbance of sufficient magnitude to permit the system to control in a soft limit cycle mode.

The parameters for the measurement of system performance are as follows:

Position, deg	±0.5
Rate, deg/sec	0 to 0.05
Disturbance torque, dyne-cm (N-cm)	100 to 1000 (0.001 to 0.01)
Thruster plenum pressure, N/cm^2	10
Propellant mass flow rate, kg/sec	0 to 3×10^{-6}
Thruster voltage, volts	0 to 2
Liquid tank pressure, N/cm^2	85
Platform moment of inertia, kg-m^2	36
Thruster moment arm, m	0.61
Thruster warmup time, sec	1
Thrusting time, fixed pulse, sec	4

The available command inputs are given in table I. Data were recorded on two eight-channel recorders and simultaneously on magnetic tape.

TABLE I. - COMMAND INPUT SIGNALS

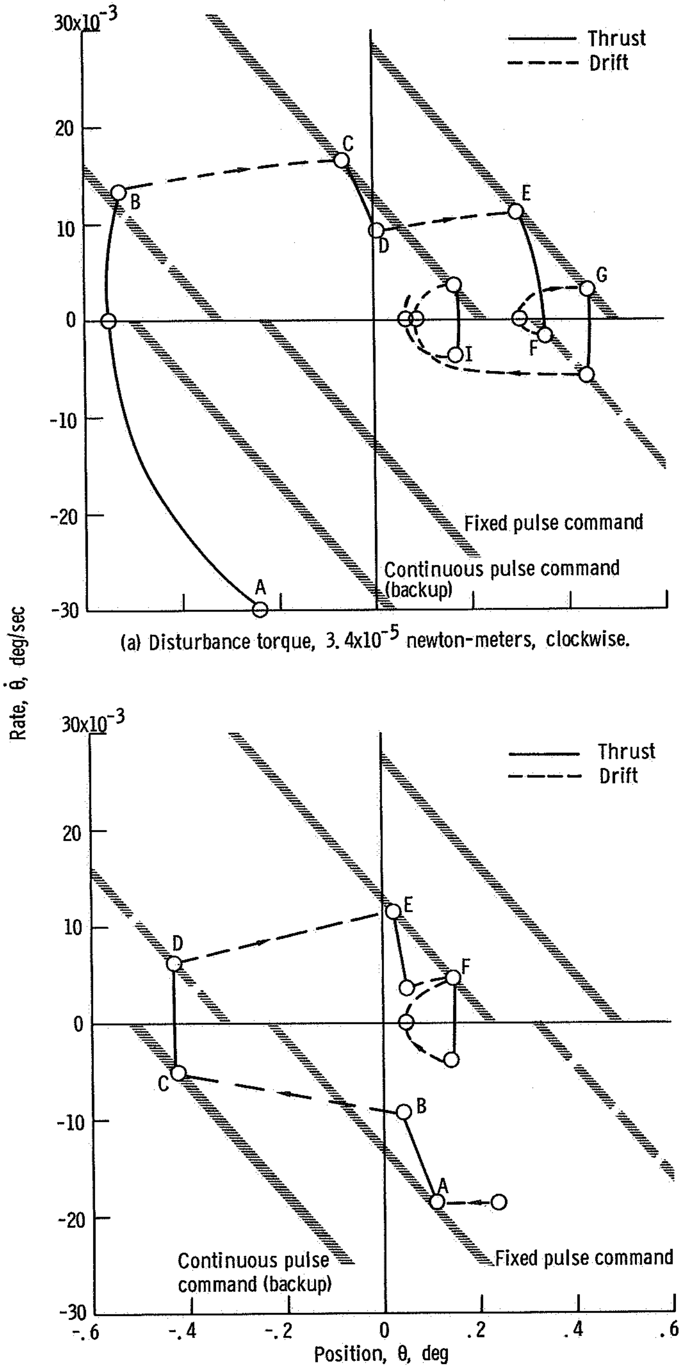
Channel	Command
1	System power on
2	System power off
3	Table clockwise slew
4	Table counterclockwise slew
5	Table on automatic control
6	Instruments calibrate

RESULTS AND DISCUSSION

Acquisition and Control

Phase plane diagrams of the acquisition and control in the soft limit cycle are shown in figures 7(a) and (b). In figure 7(a) the platform has been given an initial rate of -30×10^{-3} degree per second by command and switched to automatic control at point A. The position of A is such that the clockwise backup line has been crossed and the clockwise thruster is automatically commanded to thrust. Thrusting occurs from point A to point B where the rate has been reversed. The platform then drifts under the influence of the disturbance torque from the gas bearing to point C on the opposite inner line. A fixed pulse (C to D) is initiated at this point. However, the rate prior to thrusting is relatively high; therefore, the fixed pulse is not sufficient to lower the rate below that defined by the inner line hysteresis (not shown). Because of this, another fixed pulse is not obtained, and the platform drifts under the influence of the disturbance torque to the backup line at E and then thrusts continuously to point F. With a second encounter and thrusting at G, a rate change sufficient to subsequently enter the soft limit cycle at I is given.

Figure 7(b) depicts a situation in which the disturbance torque is somewhat higher. The system has been switched to automatic control prior to point A with a rate of -19×10^{-3} degree per second. One encounter (A to B) of the clockwise inner line, which did not lower the rate below the hysteresis value, and the clockwise backup line (C to D) are sufficient to reverse the table rate. Again the table drifts under the influence of the disturbance torque to E where a fixed pulse is initiated. In this case the rate at E is such that the 4-second pulse is sufficient to drive the rate below the hysteresis value, thus obtaining a second pulse at F. This pulse is sufficient to drive the system into the soft limit cycle. The range of the sensor did not permit a much larger variety of initial conditions.



(a) Disturbance torque, 3.4×10^{-5} newton-meters, clockwise.

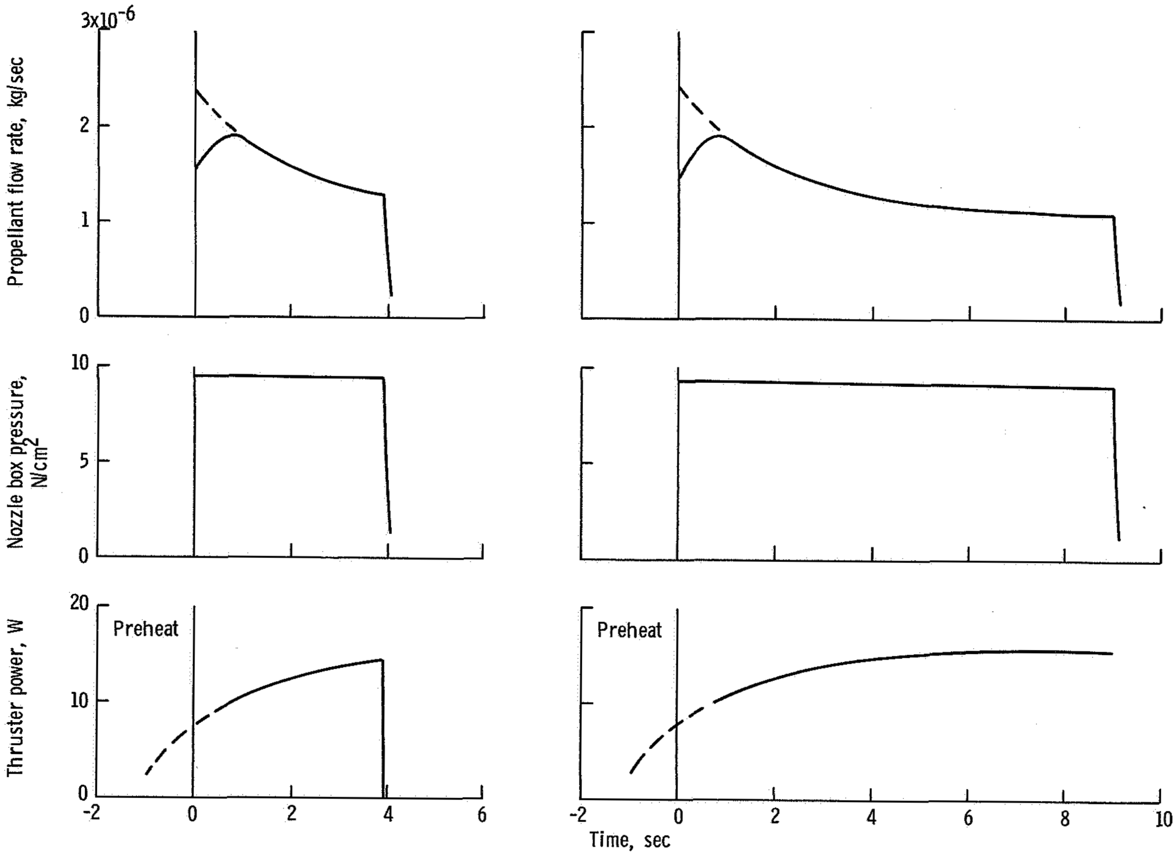
(b) Disturbance torque, 5.8×10^{-5} newton-meters, clockwise.

Figure 7. - Acquisition and limit cycle operation. Control torque, 10^{-3} newton-meters; table moment of inertia, 36 kilogram-meters squared.

Thruster Performance

The instantaneous values of propellant flow rate are shown in figure 8 for a typical fixed pulse of 4 seconds (fig. 8(a)) and for a somewhat longer pulse of approximately 9 seconds (fig. 8(b)) which represents a backup pulse. The data are for a fixed preheat time of 1.0 second and an average nozzle box pressure (i.e., pressure upstream of the thruster heater tube) of 9.4 newtons per square centimeter. The mass flow decreases with increasing time as a result of the increase in thruster power which is reflected in an increase in the wall temperature of the thruster heater tube. As temperature increases, the friction losses and change in density combine to reduce the propellant flow rate until equilibrium results at some time in excess of about 7 seconds (fig. 8(b)). Thereafter, the mass flow is a function only of the nozzle box pressure, which decreases slightly as propellant is withdrawn from the plenum tank.

For times less than 1 second the flow rate is indicated by the dashed line which was drawn in accordance with the nozzle box pressure and the results of references 1 and 3



(a) Fixed pulse.

(b) Backup pulse.

Figure 8. - Thruster transient performance.

where direct propellant mass flow rate measurements were obtained for a similar thruster. In the present study, values indicated by the instrumentation were somewhat below the curve for times less than 1 second as a result of the location of the subsonic orifice used in the measurements. The orifice was considerably upstream of the thruster. If the orifice were located closer to the thruster, the measurement would be expected to follow the dashed curve.

The results of the instantaneous flow rate measurements were used to calculate the average propellant mass flow rate, which is shown in figure 9(a) as a function of pulse width. The average mass flow rate shown was calculated from

$$\dot{m}_{av} = \frac{\int \dot{m}\, dt}{\Delta t}$$

The average propellant flow rate decreases with increasing pulse width.

The average thrust is shown in figure 9(b) and was obtained from the change in angular rate of the platform and known values of moment of inertia and moment arm. Average thrust decreases with increasing pulse width. Again, flow losses in the heater tube combined to reduce the total pressure upstream of the thruster nozzle inlet and thus decrease thrust. Average thrust decreases from about 2.1 millinewtons for a 4-second pulse to 1.6 millinewtons for a pulse width of about 20 seconds, a decrease of 24 percent. Similar results have been reported in references 1 and 3.

These data for the propellant mass flow rate and thrust were obtained for a fixed thruster preheat time of 1 second. An increased preheat time would be expected to reduce the maximum variation of thrust and propellant flow rate, although the reduction would be at the expense of higher average power. If required, the preheat time may be controlled such that the variation of thrust with pulse width may be considerably reduced.

The data of figures 9(a) and (b) were used to obtain the variation of average specific impulse with pulse width shown in figure 9(c). Average specific impulse increases with increasing pulse width primarily because of the higher average temperature achieved.

Although not shown explicitly in the foregoing results, the performance parameters (i.e., thrust and propellant flow rate) were found to be dependent on duty cycle. If the thruster off-time is not sufficient to allow for complete cooling, adjacent pulses will not be identical because of the difference in the temperature history of the heater tube during the pulse. Higher duty cycles (closer pulse spacing) tended to lower the mass flow and thrust and to increase the specific impulse.

The foregoing results for thruster performance indicate that the propellant

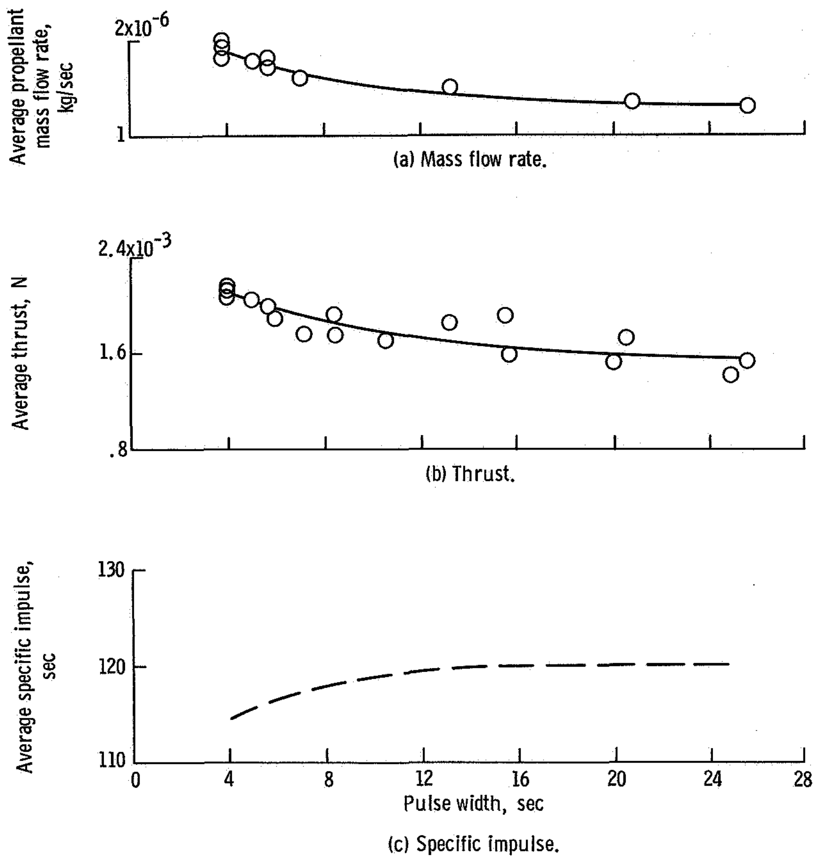


Figure 9. - System average performance.

consumption for a given impulse requirement, particularly in the attitude control mode (where short pulses are assumed), may be a rather strong function of the choice of pulse width for realistic preheat times.

CONCLUDING REMARKS

Performance data for a resistojet system to be used for the attitude control and station keeping of a stable platform satellite were obtained in a simulated operational environment. The system was shown to be capable of acquiring a position and maintaining a specific attitude of accuracy of $\pm 0.2^{\circ}$ about a single axis. It was found that the performance parameters, mass flow rate, thrust, and specific impulse, were all significantly affected by preheat time and pulse width. Increased preheat and pulse width times caused decreased mass flow rate and thrust and increased specific impulse.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 17, 1968,
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