IUS THRUST VECTOR CONTROL (TVC) SERVO SYSTEM

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ABSTRACT

The IUS TVC SERVO SYSTEM, currently in full-scale development, consists of four electrically redundant electromechanical actuators, four potentiometer assemblies, and two controllers to provide movable nozzle control on both IUS solid rocket motors. The system contains two unique design areas: the use of "mirror-image" potentiometers opposite the actuators on the nozzle to increase system accuracy under varying conditions and the use of a pair of solenoid-operated gears normally meshed with the rotor gear to provide a redundant position lock. Test data obtained to date show excellent performance of both items.

INTRODUCTION

This paper presents an overview of the more severe IUS TVC servo system design requirements, the system and component designs, and test data acquired on a preliminary development unit. Attention will be focused on the unique methods of sensing movable nozzle position and providing for redundant position locks.

DESIGN CRITERIA

The design criteria for the system are shown in Table I. Of particular interest is the requirement to meet all performance parameters under the two significantly different sets of mounting geometries and loads of both stages of IUS solid rocket motors. In addition, the system was to be configured in a standby redundant manner such that a maximum number of failures in the primary contoller or actuator could be detected and corrected by switching to the backup controller/actuator. The entire system is built to the reliability requirements of SAMSO-LVGS-77-005 and SAMSO-STD-73-2C.

DESIGN DESCRIPTION

System Description

The servo system was configured as shown in Figure 1. The controllers are located in the forward compartment of the second stage of the two-stage vehicle; two actuators and two potentiometer assemblies are mounted between

TABLE I

Parameter	Requirement
Input Power	31 amps/axis max at 24-32 Vdc
Stroke	10.2 cm (4.014 in.)
Stall Force	2.8 kN (630 lbf)
Accuracy	±1.6 mm (±.063 in.)
Frequency Response	>6 Hz at 100° phase lag
Weight, Actuator	5.58 kg (12.3 Lbm)
Reliability	>0.99988 redundant drive trail
	>0.999972 single thread element
Operating Temperature	-34°C to +71°C

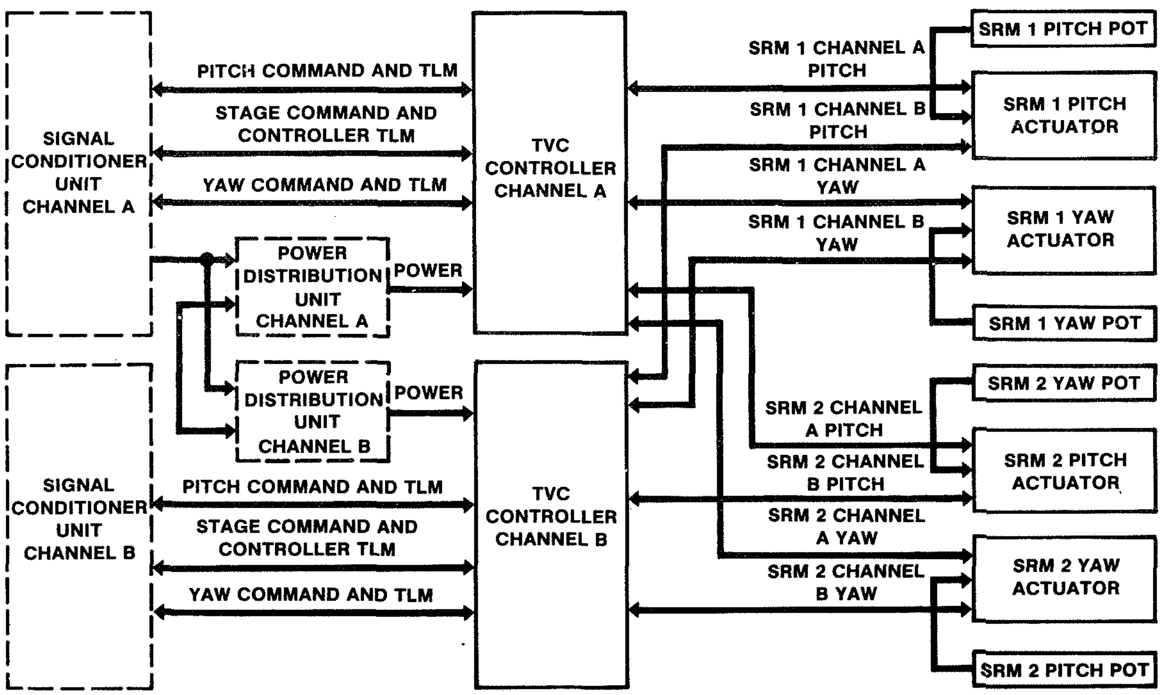

Figure 1. IUS TVC Servo System
Block Diagram

the structure and movable nozzle of each rocket motor. Each controller contains drive and control circuitry for the four actuators. Each actuator contains redundant drive motors, redundant potentiometer feedback elements, and the redundant position lock mechanism.

As shown in Figure 2, the mounting of the actuators and potentiometers is unusual in that the bracket and actuator are configured to form a ball-and-socket connection at the output shaft end, as opposed to a rod end bearing at the rear. This arrangement greatly reduces the bracket weight but tends to increase nozzle cross-coupling errors. Due to these errors and those induced by nozzle axial motion and thermal growth, the potentiometer assemblies were added to the nozzle opposed from the actuators. These potentiometers are identical to those in the actuators and contain two electrically independent feedback elements.

The output of the primary element is electronically summed within the controller with the primary output from the actuator as a measure of nozzle deflection angle. As shown in Figure 3, this arrangement yields very low (0.5%) kinematic errors, and when combined with all other errors results in a maximum error of 1.7%. For comparison, an actuator mounted normally to the nozzle centerline, and without the "mirror-image" potentiometer would have kinematic errors of approximately 5% alone. In addition, environmental temperature changes, nozzle thermal growth, and cross-axis coupling would all introduce errors which are essentially nonexistent with the "mirror-image" approach.

Actuator Description

The actuator shown in Figure 4 contains two rare-earth dc torque motors mounted directly on a ball nut. Both ends of the screw are supported by guide bushings; the nut is supported by a spherical roller bearing. The spherical roller bearing is used, as opposed to ball or roller types, to provide for any possible misalignments between the ball screw and ball nut. The dual-element potentiometer is radially supported on its shaft end by a bushing that slides on the bore of the ball screw and on its aft end by the rear housing of the actuator. The rear housing also provides a bearing surface for the rear guide of the ball screw and the mounting surface for the position lock. All bushings are machined from Delrin AF 113, several of which contain radial slots for thermal growth considerations. The ball screw, bearing, locking gears and solenoid poppets are lubricated with Lubeco M390. All assemblies are vented via stainless-steel mesh cloth to satisfy the program's qualification test requirements.

Position Lock

The position lock shown in Figure 5 consists of two solenoid-retracted gears in mesh with each other and a gear integral with the ball nut. With the solenoids unactivated, return springs inside the solenoids hold the gears in mesh with the ball nut gear. Upon energization of the system avionics power, the primary and backup controllers apply full voltage to both the primary and

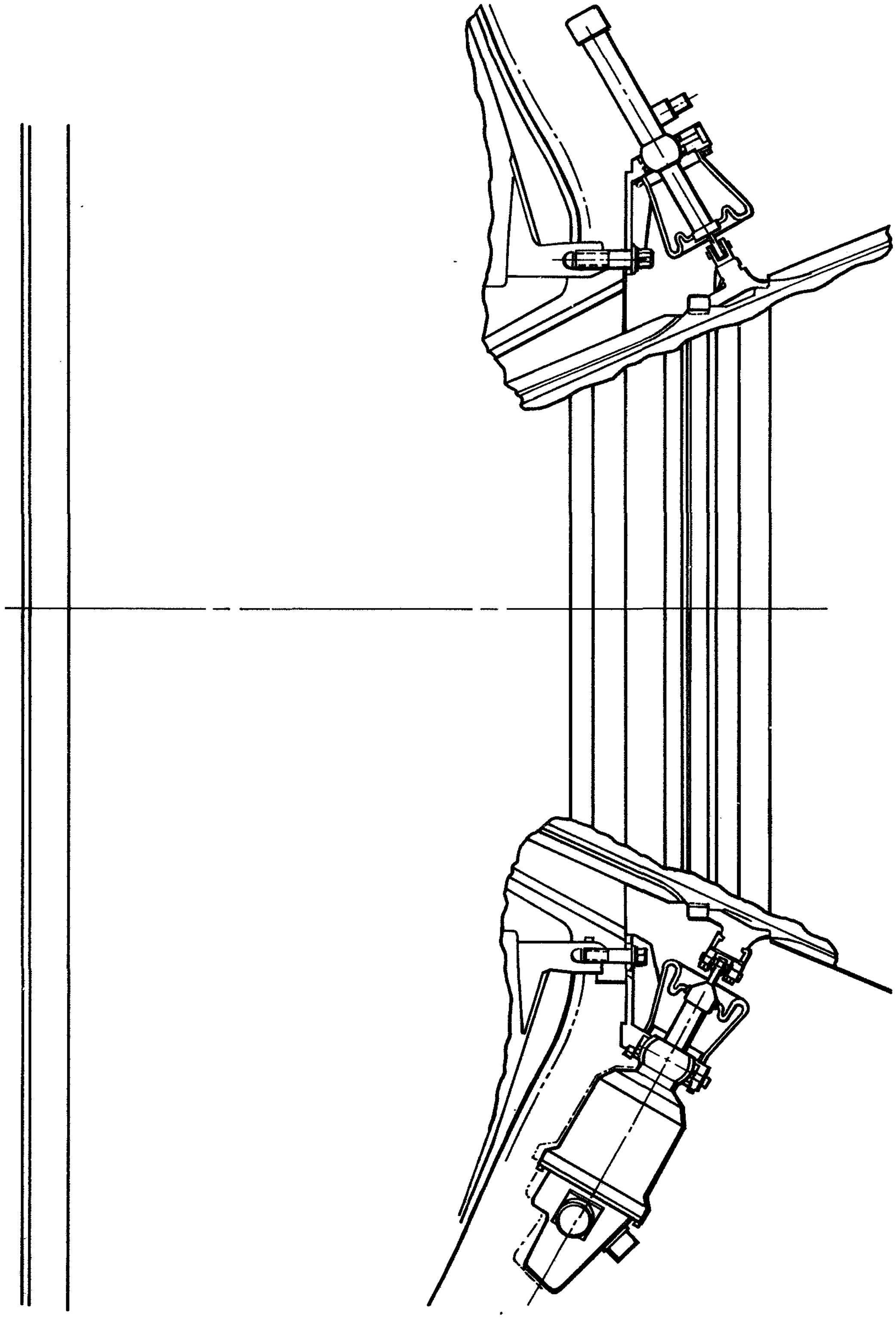

Figure 2. Actuator and Potentiometer Mounting

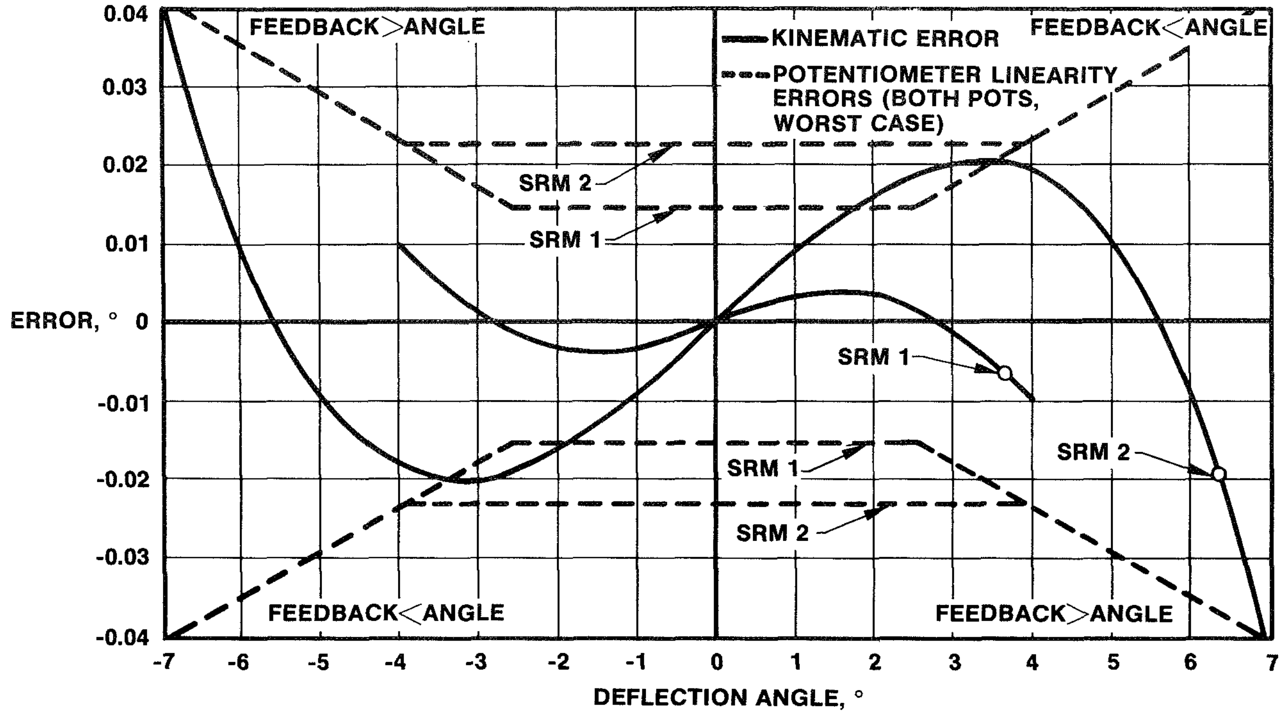

Figure 3. System Kinematic Errors

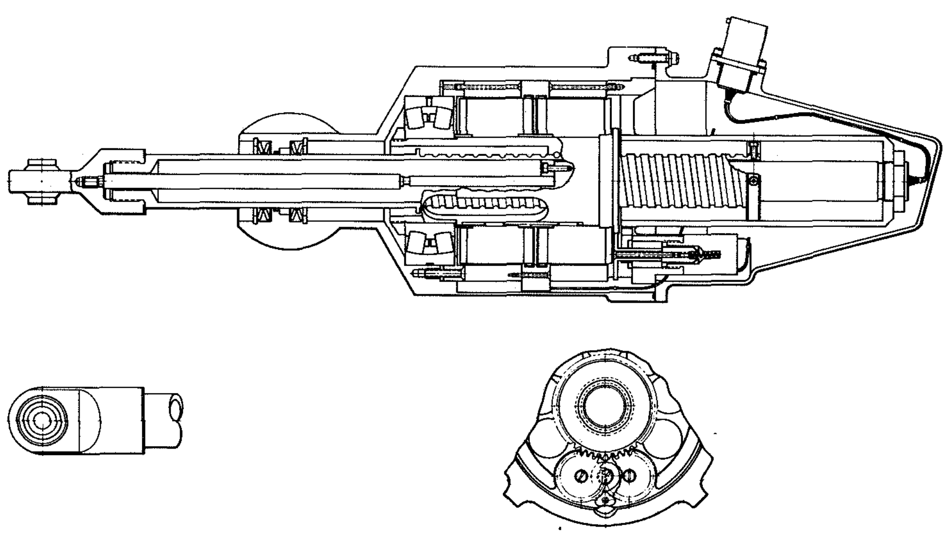

Figure 4. Actuator Assembly

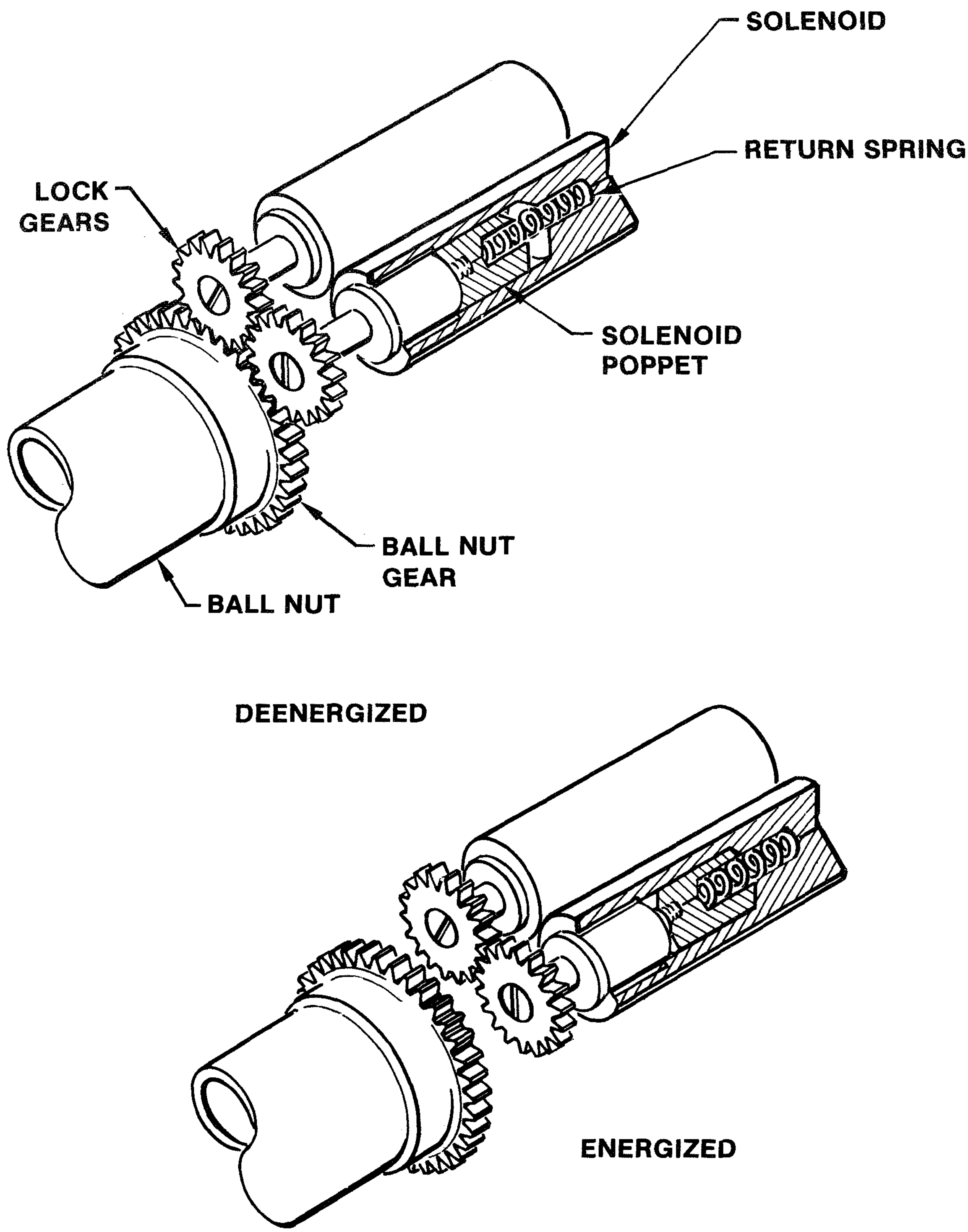

Figure 5. Position Lock Mechanism

backup solenoids for approximately 25 ms, and then switch back to a holding voltage level of 4.0 Vdc to reduce solenoid internal heating. During the 25-ms full-power time period, the solenoids retract the gears against the sum of reflected nozzle loads and the return springs. Both lock gears are supported by bushings in the rear housing.

Since both gears are independently activated and independently spring-loaded, this method is redundant in terms of unlocking and inadvertent relocking. During energization, the failure of one gear to retract has no effect on the other, resulting in the failed gear remaining in mesh with the ball nut gear, and the operative gear being retracted out of mesh. Since the gears are free to rotate, the unretracted gear is merely rotated as the actuator operates. Protection against inadvertent relocking is provided by the independent solenoids. A failure of either solenoid to maintain holding force allows the return spring to remesh the gear, resulting in one meshed and one unmeshed gear.

DEVELOPMENT DATA

Figure 6 shows the assembled and exploded views of the preliminary development unit. This unit was performance-tested on a load test fixture that simulated the kinematics and all load constituents of the stage 2 movable nozzle.

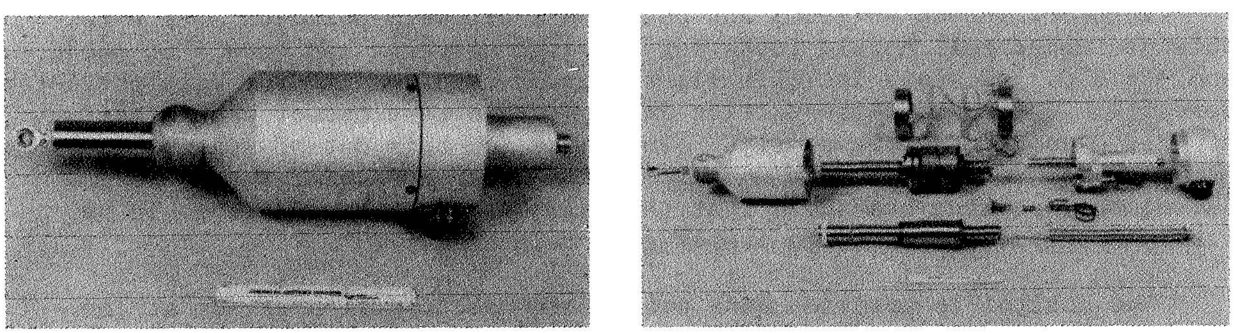

Figure 6. Preliminary Development Unit

Dynamic Performance Data

Figures 7 and 8 present the small- and large-amplitude frequency response data obtained at nominal input voltage and at the maximum expected nozzle loads. Data obtained at miminum input voltage result in a slightly higher break point on the small amplitude command and no significant change for the large amplitude.

Figure 9 presents step response data taken at -23°C with minimal nozzle load. The linear velocity profile is governed by a slew rate limiting circuit within the controller, which was set to 26.4 cm/s for this testing. As shown, the system overshoot is minimal.

STEADY-STATE PERFORMANCE DATA

Table II presents a comparison between the requirements and test results for several steady-state parameters. The stiffness and backlash data were obtained with the locking gears in their normal deenergized position. The stiffness data was taken over the load range of 0 to 2.22 kN (500/Lbf), although the locking gears are structurally sized for loads of up to 6.2 kN (1400) Lbf). Also shown in Table II are the worst observed results taken for the lost motion prior to actuator relocking and actuator unlocking time. The lost motion prior to relocking is very small, equal to the allowable backlash of the system. The unlocking time is also very small, well below the 25 ms full power application time of the controller.

Accuracy Data

Both command-to position and position monitor-to-position data were obtained under full nozzle loads for actuator temperatures of -23°C, +21°C, and +48.8°C. As shown in Table II, the error requirements for both parameters were ±1%. The command-to-position data obtained were out of specification at 48.8°C and nearly out at 21°C. The cause for this out-of-specification performance was traced to an open loop gain which was lower than modeled. Subsequent modeling has shown that the command-to-position data would be within specification had the proper gain been used.

The monitor-to-position data was within specification except at low temperature. The cause for this was not pursued.

All of the accuracy testing included the effects of loads, kinematics, frictions, etc., and were obtained from dial indicator readings taken on the nozzle simulator. This data was then used to calculate the actuator position.

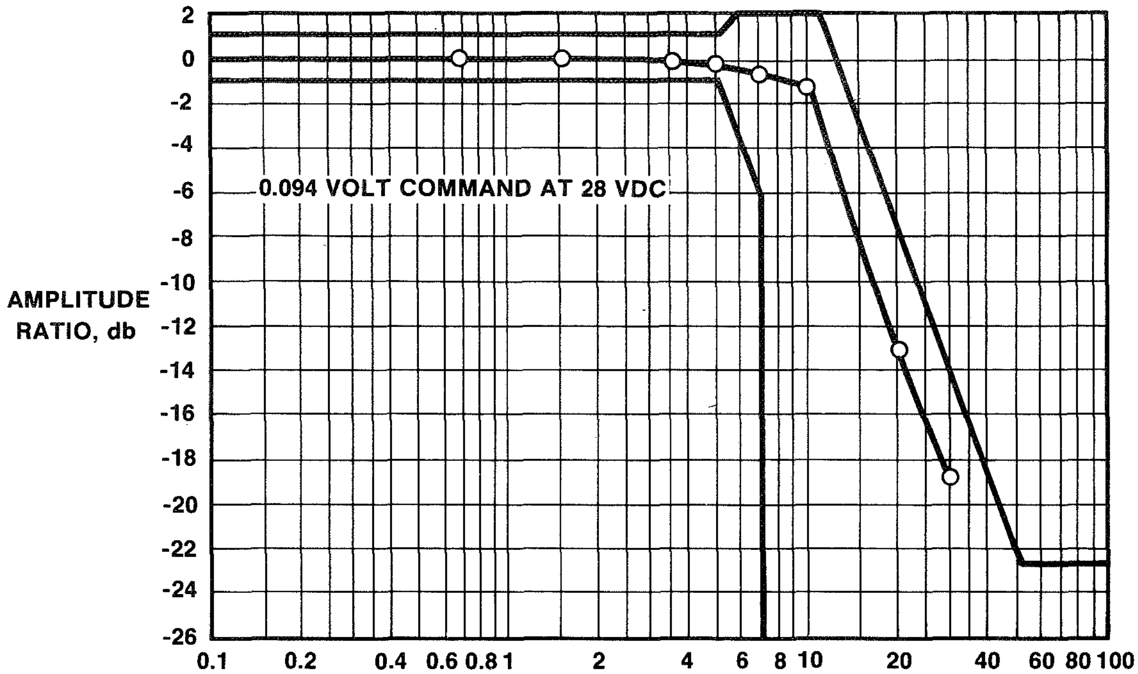

Figure 7. Small Amplitude Frequency Response (±2.4% Stroke)

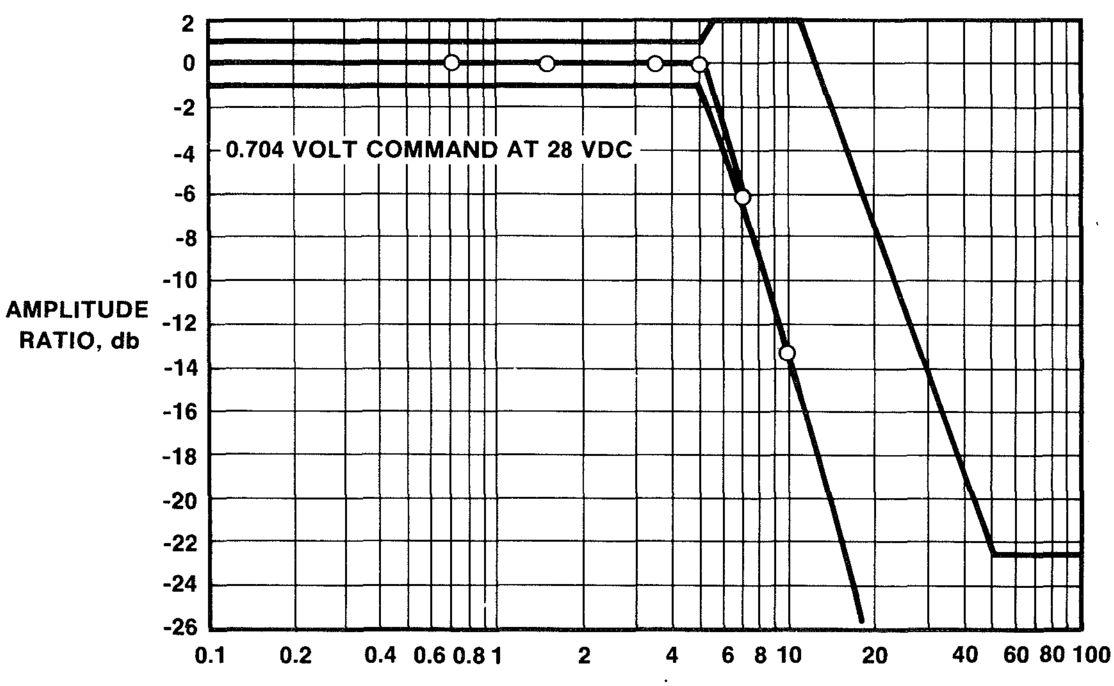

Figure 8. Large Amplitude Frequency Response (±18% Stroke)

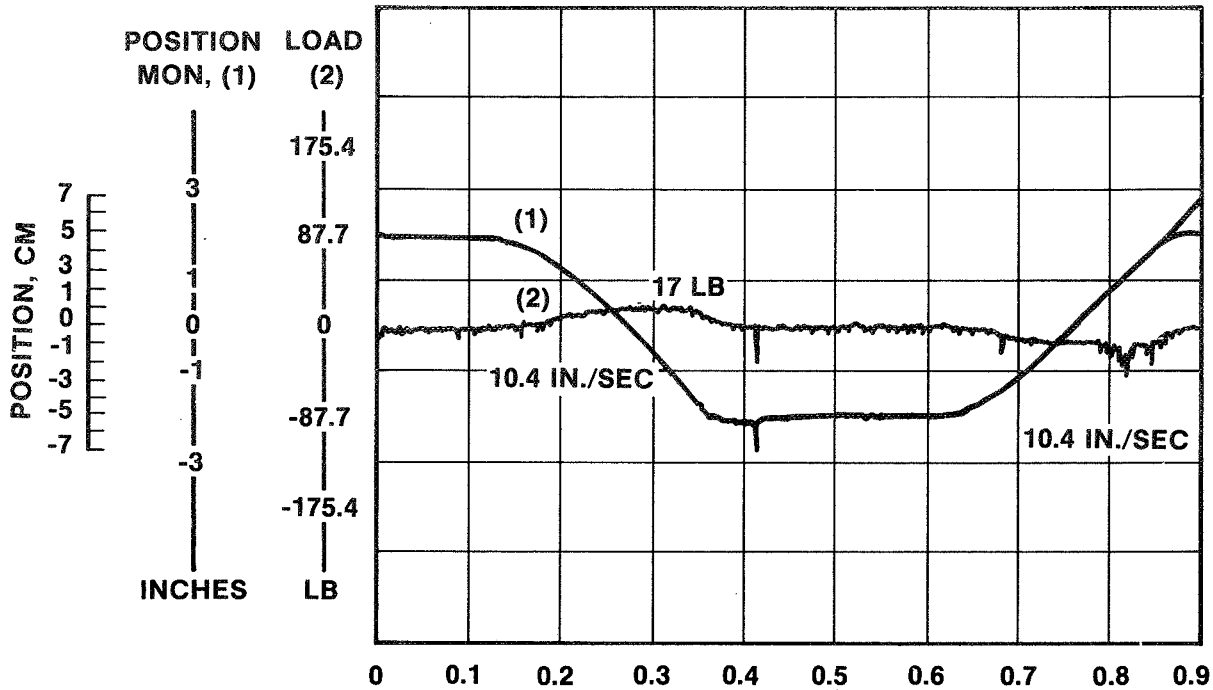

Figure 9. $-23^{\circ}C$ Step Response Data

TABLE II

Parameter	Requirement	Test Results
Stiffness	4377 kN/m (25,000 Lb/in.) minimum	7581 kN/m (43,300 Lb/in.)
Backlash	(0.254 mm) (0.010 in.) maximum	0.208 mm (0.0082 in.)
Relock lost motion	-	0.251 mm (0.0099 in.)
Unlock time	-	0.006 s
Command-to-Position Error	±1%	1.0% 21°C 1.5% 48.8°C 0.05% -23.3°C
Monitor-to-Error Position Error	±1%	0.1% 21°C 0.25% 48.8°C 1.2% -23.3°C

CONCLUSIONS

In conclusion, both the use of "mirror-image" potentiometers to increase system accuracy and the use of duplex gears to affect a position lock have been successfully developed and demonstrated.