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Electromechanical Rotary Actuator

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Abstract

An electromechanical rotary actuator has been developed as the prime mover for a liquid oxygen modulation valve on the Centaur Vehicle Rocket Engine. The rotary actuator requirements, design, test, and associated problems and their solutions are discussed in this paper.

Introduction

This electromechanical rotary actuator, shown in Figure 4, has been successfully developed as the prime mover for a liquid oxygen valve. The unit is required to provide angular positioning of the liquid oxygen flow control valve on the Centaur Vehicle Rocket Engine. The application requirements are stringent. The unit must operate fully at cold temperatures and during vibration.

The unit was designed to meet specific customer needs. The design is fully developed, qualified and has flown on at least three missions (6 units). Design, performance, and qualification test problems are presented.

Design Requirements

The rotary actuator is required to modulate the flow of liquid oxygen (LOx) during rocket engine firing in order to optimize the fuel consumption. The application environment is severe; extreme cold temperature operation due to the close proximity of -184°C (-300°F) LOx and high, sustained vibrational loading due to rocket engine operation. The application requirements/unit capabilities are listed in Table 1.

Table 1 - Rotary Actuator Performance Requirements

Weight max.	2.08 kg (4.6 lbm)
Supply Voltage	28 VDC
Stall Current max. (supply limited)	0.45 A
Winding Resistance Phase to Phase	48 Ω
Output Rotation	2.44 rad (140 deg)
Step Size	0.32 mrad (0.0187 deg)
Running Torque @ 28 VDC & 0.13 $^{rad}/_{s}$	11.3 N•m (8.33 ft•lbf)
Unpowered Holding Torque min.	2.26 N•m (1.66 ft•lbf)
Operating Temperature Range	-64°C to +76°C (-83°F to +169°F)
Random Vibration Level	22.6 Grms

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Mechanical Design

The rotary actuator consists of a three-phase small-angle stepper motor, a Harmonic Drive gear reducer, a duplex bearing pair, dual-ganged instrumentation potentiometers, and associated hardware all mounted in an appropriate housing. The actuator envelope is given in Figure 1. A layout of the device is given in Figure 2.

Motor

The motor is a three-phase, 1.5-degree stepper having a wound stationary member and a permanent magnet rotating member. The motor current was limited by the customer-supplied electronic controller. The motor parameters are given below.

Table 2 - Motor Parameters

Resistance - Phase to Phase	48 ± 10% Ω
Inductance	16 ± 30% mH
Running Torque @ 10.4 rad/s	2.4 N•mm (3.5 in•oz)
Voltage Range	22.5 to 32 VDC
Current	0.44 A

Gear Train

The 80:1 gear reduction is accomplished with a Harmonic Drive device which consists of a wave generator as the input member, a circular spline as the fixed member and a flex spline as the rotating output member.

Instrumentation

The actuator has two potentiometers that provide position feedback. The potentiometers sense the actuator output position by providing a voltage signal proportional to output position. The potentiometers are driven directly by the output shaft through an anti-backlash coupling. Characteristics of the potentiometer are:

Potentiometer Parameters	
Resistance	5000 ±10% Ω
Linearity	0.5% absolute
Power Rating	1.25 W

External visual shaft position was also provided for purposes of integrating the actuator with the valve. Shaft position is given by a scale graduated in 0.017 rad (1 deg) increments.

Bearings

The actuator output shaft rotates on a pair of 440C stainless steel preloaded ball bearings. The bearings are mounted in a face to face arrangement. This mounting is preferred in cases where the housing operates at a higher temperature than the shaft and has a lower moment of stiffness. The lower moment of stiffness helps reduce radial loads induced by the actuator onto the valve shaft. The motor rotor is mounted in stainless steel shielded ball bearings.

Mechanical Stops

Adjustable mechanical stops were provided for purposes of integrating the actuator with the valve. The stops are external and independently adjustable in increments of 0.017 rad (1 deg). The stops are capable of withstanding the full actuator torque without damage to the unit.

Heater

Because of the connection to a liquid oxygen valve, the unit was mounted to the valve through a thermal isolator (not shown). A heater was provided to keep the unit within the required operating temperature. A hermetically sealed thermostat was used to close the heater circuit when the unit temperature dropped below -17.8°C (0°F).

Materials

Because the unit is mounted to a LOx valve, failure of the valve seal could allow LOx into the actuator. As a result, the housing and shaft material were chosen for LOx compatibility. The housings are made from 6061-T6 aluminum. The shaft and Harmonic Drive are made from 304L stainless steel.

Lessons Learned

During the development and qualification tests several problems occurred which required corrective action. The most significant of these were encountered during the vibration and thermal cycling tests, where the actuator was required to meet functional performance requirements. The investigations and the corrective actions were complicated by the arrangements of the tests, since thermal cycle testing always followed vibration. An important corrective action for a problem exposed during thermal cycling was actually caused during vibration. Listed below were the significant lessons learned during the Development and Qualification Testing.

a) Motor current limit

Since the motor current is limited by an electronic controller and not the motor winding resistance, the developed motor torque remains constant over temperature. The customer required that the current limit be bracketed within ±10%, meeting the minimum torque requirement at minimum current and voltage, and not exceeding a maximum of 33.9 N•m (25 ft•lbf) at maximum current and voltage. Extensive testing at cold temperature was required to determine the minimum current value required to compensate for the variation in internal friction with temperature and still meet the performance goals.

As part of the cold temperature study, several motor and actuator parameters were characterized. The drag torque of all rotating components in the actuator were quantified and assessed for impact on the motor torque producing capability. This study was done at ambient conditions and at various temperatures down to -67.8°C (-90°F). The viscosity of the bearing and geartrain lubricant (Bray 601 grease) increased significantly at the colder temperatures, which resulted in an unacceptable increase in bearing and geartrain drag torque. These increases were anticipated during the design stage but the actual increases were higher than expected. The drag torque of the output bearings and seal, nearly doubled over the temperature range. The rotor and harmonic drive wave generator bearing drag, likewise, increased 300% over the temperature range, and was dependent on rotor speed. Since the drag torque of components on the output side of the geartrain is decreased by the gear ratio, the effect on the motor rotor is small. If drastic decreases in drag were to be obtained, they had to come from the input side of the geartrain, i.e. motor rotor and harmonic drive bearings.

Significant improvement in the input drag torque was obtained by changing the lubrication from grease to oil. The type of lubrication for the rotor and harmonic drive bearings was changed to oil (Bray 815Z) and testing was repeated. A reduction in the motor drag torque greater than 50% was realized with oil as the lubricant. Still, further improvements were necessary in order to gain margin for qualification testing. It was discovered that by controlling the amount of oil in the wave generator bearing (the largest contributor to drag) the necessary improvements to performance were attained. Two other changes were implemented at the same time, which were minor in drag reduction as compared to the lubrication change. The seal's outside diameter was reduced by 0.127 mm (0.005 in) to lessen the circumferential force on the output spline. This change amounted to a potential 5% decrease in motor drag. The other change was to position a bearing grade material between the wave generator and the aluminum rotor shaft, where the two components previously contacted each other.

b) Potentiometer cover standoff fracture.

The potentiometer cover is removable and is attached to the actuator body via two standoffs. During vibration the standoffs fractured at the base of the thread. The cover was loosely fitted to the housing at the interface which allowed the cover, with the standoffs and fasteners rigidly attached, to move during vibration. This movement, increased the loading at the undercut of the standoff's thread to the point where it exceeded the material strength and fractured. The cover, standoffs and fasteners fell from the unit as an "assembly".

This problem was corrected by revising standoff installation torque to fit the material strength and bonding the cover to the housing.

c) Potentiometer resistance variation.

The dual-ganged potentiometer is connected in parallel for telemetry information during flight. The previous valve actuator, using basically the same potentiometer, was tested in this same parallel arrangement. For this actuator, the customer wanted to measure the output of each cup of the potentiometer to ensure that the redundancy of the potentiometers were still intact. In resistance variation testing of the potentiometer (the unit is powered, but not stepped), the response of each cup of the potentiometer was measured during vibration. The proper potentiometer response during the vibration would be to show no variation in the voltage (resistance) output. The limit for resistance variation, however, was 300 ohms.

During the qualification vibration testing, one cup of the potentiometer measured well within the 300-ohm limit, while the other cup showed ever increasing resistances as the level and vibration time increased. A test performed in the parallel arrangement, as done previously, would have indicated a resistance variation of less than the 300 ohms. Instead, the variation in the affected cup was shown to be clearly erratic. The cause of the erratic variation was found via X-ray and in the subsequent potentiometer teardown. One of the three wipers which contacted the circumferential element had broken off, leaving the two other wipers to contact the element. The wiper assembly was found to have nicks and dents, where the wipers were adjusted and trimmed. The wiper which broke off, fractured at an unintentional trim crease. Later, after discussing the matter with the potentiometer vendor, it was discovered that the wiper assembly was a new, cost saving, better linearity, precious metal stamping, which had been introduced into the potentiometer several years prior to this date. They informed Honeywell that the stamping had failed to live up to all of the expectations and that the wiper assemblies were now fabricated from precious metal wire as was done previously.

It was reassuring to know that the assemblies would no longer fracture, however, resistance variations in potentiometers remained a problem. Typically, one cup of the potentiometer would have excessive variation, while the other was within specification. Because the potentiometer had so many variables that could affect the resistance variation (bearing/shaft clearances, bearing preload, wiper pressure on the element, axial play, material resistivities, etc), the potentiometer vendor was directed to screen the potentiometers using the same test technique as would be employed on the end item actuator. The resistance variation limit for the potentiometer, tested alone, was reduced to 40% of the end item acceptance test limit to account for response magnification when mounted on the unit.

d) Rotor shaft bearing shoulder

After the qualification level vibration testing, the unit failed to meet the required speed and torque load points. Disassembly of the unit revealed excessive wear on the rear rotor bearing shoulder and outside diameter. The vibration time and level had deformed the bearing shoulder, shifting the position of the rotor shaft greater than 0.254 mm (0.010 in). The rear of the rotor contacted the output side bearing mount, input rubbing against output, increasing the input drag torque to excessive levels.

The aluminum rotor shaft construction has slots machined along the axis of rotation, which transfer torque from the motor to the Harmonic Drive coupling. These slots reduced the shaft area moment of inertia and stiffness. Consequently, during vibration the shaft flexure contributed to the wear and degradation of the shaft bearing shoulder.

It was further discovered that the reduced stiffness of the rotor shaft was responsible for some of the problems seen in thermal cycling. Evidence of rubbing contact between the motor rotor and the stator had been seen on the qualification unit after the initial cold temperature failure.

The problem of the bearing shoulder was corrected by inserting a high strength steel spacer between the bearing shoulder and the rotor shaft shoulder. Figure 3 shows the revised rear motor bearing configuration. The spacer has two tabs that are machined to tightly fit the slotted shaft. The purpose of these tabs is to stiffen the rotor shaft and limit its deflections.

The potential for rotor and stator contact was decreased by the addition of this spacer. However, inspection of parts revealed a high runout condition in the rotor assembly. The condition was due to the manufacturing tolerance buildup of several parts in the assembly. The corrective action for this condition was to machine (grind) the rotor assembly as an assembly. The changes also resulted in more consistent motor performance during thermal cycling.

e) Potentiometer signal noise.

During the qualification testing, the unit was required to undergo a temperature / humidity test. In this test the unit is subjected to high moisture levels for extended periods of time (hot and humid Florida climate). After the temperature/humidity test, the unit was subjected to a final Thermal Vacuum Test. The first temperature extreme was the cold temperature limit -63.8°C (-83°F). While monitoring each cup of the potentiometer, testing at this cold temperature produced erratic signals from one of the potentiometer cups. The other cup showed nominal behavior at cold temperature, and both functioned properly at warmer temperatures.

This problem was caused by the influx of water vapor (humidity) into the non-hermetically sealed potentiometer. This was corrected by vacuum baking the actuator after all unit acceptance tests in order to drive off any excess moisture. The bake cycle prevents moisture from condensing and freezing on the potentiometer elements and causing the electrical noise. Special handling instructions and storage in nitrogen purged packaging were added to the actuator assembly procedure to promote the humidity free state until the actuator is ready for the customer's installation.

Each of the above problems were sequentially identified during the qualification testing and were successfully corrected. The rotary actuator was tested for a total of 40,000 rotational cycles for a nine (9) cycle mission simulation.

Conclusion

The rotary actuator was designed, built and tested to satisfy specific customer requirements. The missions requirements included working conditions of high level vibration, rapid temperature/pressure changes and extreme temperature levels. The testing program verified the unit's capability to meet the challenging mission requirements. The unit has been successfully used on at least three launches.

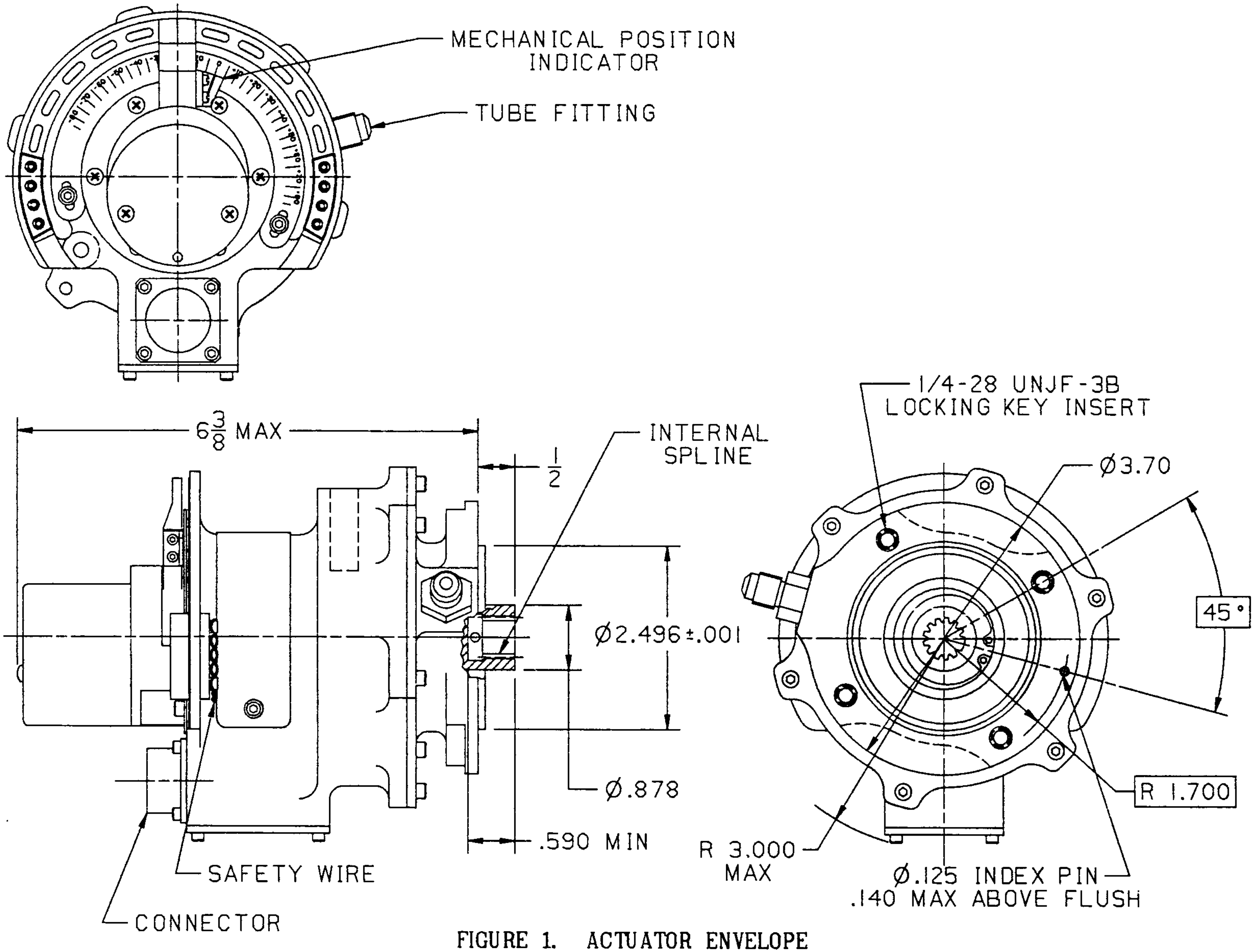

FIGURE 1. ACTUATOR ENVELOPE

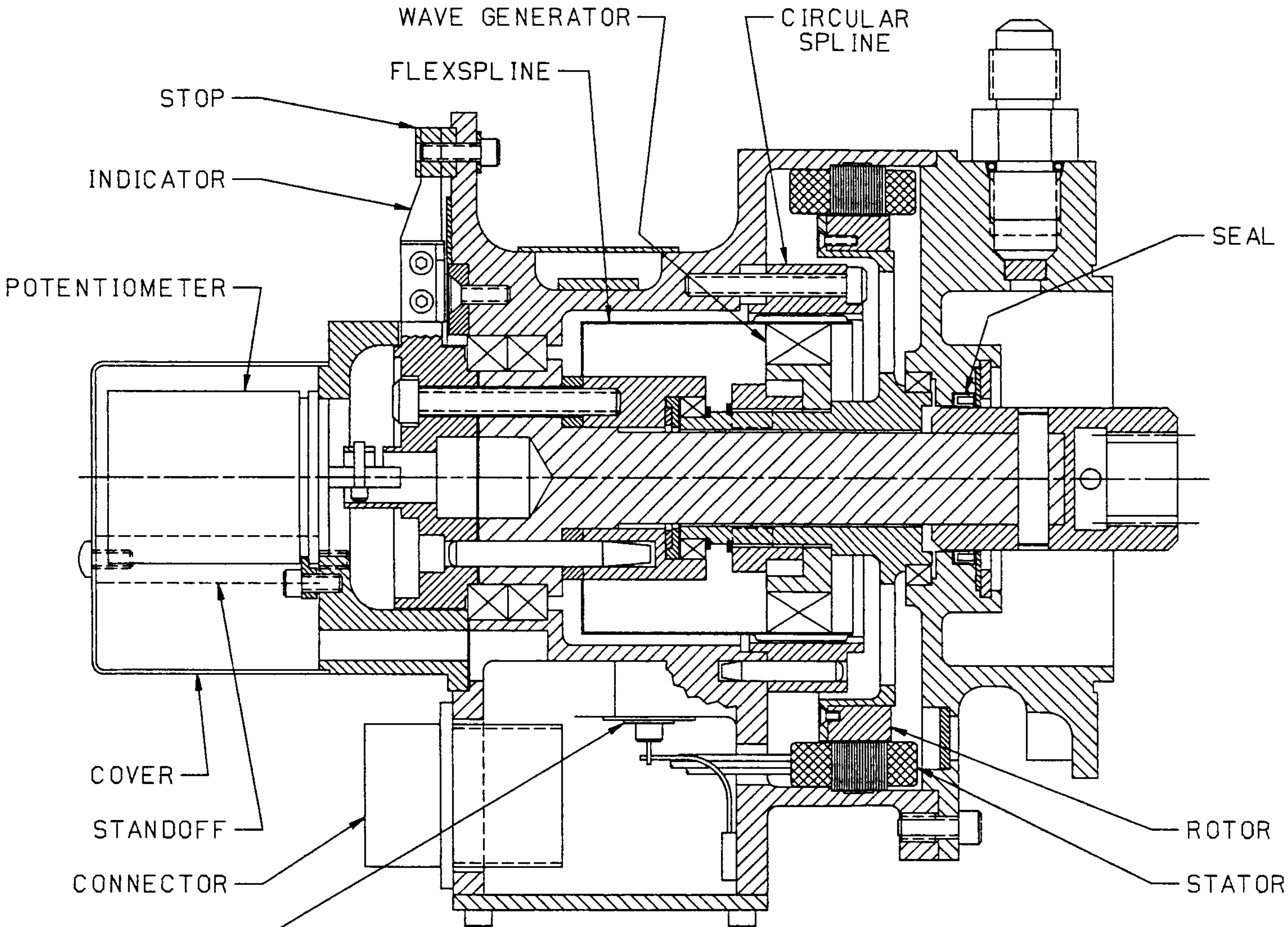

FIGURE 2. ROTARY ACTUATOR PN 2961041

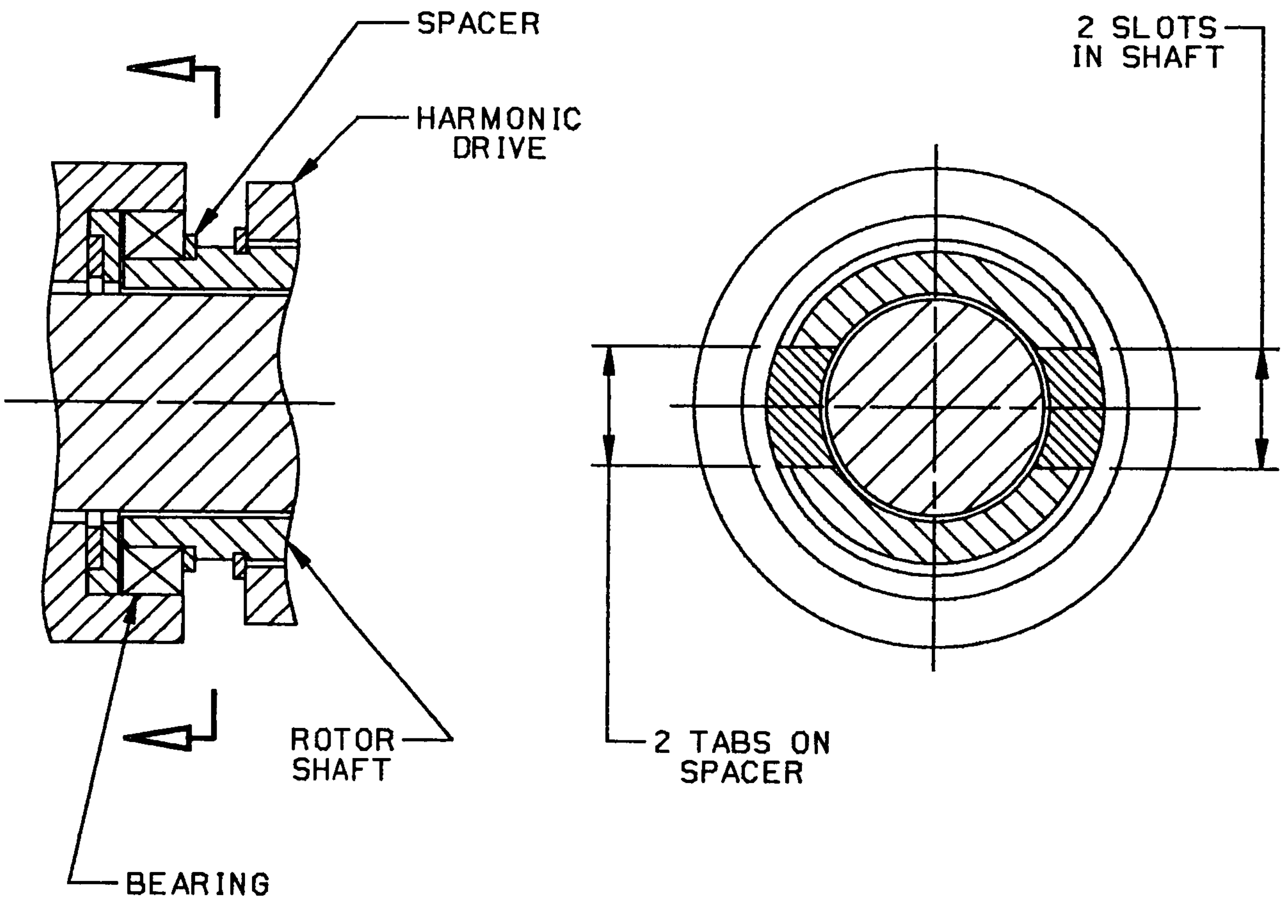

FIGURE 9. ROTOR SHAFT DETAIL

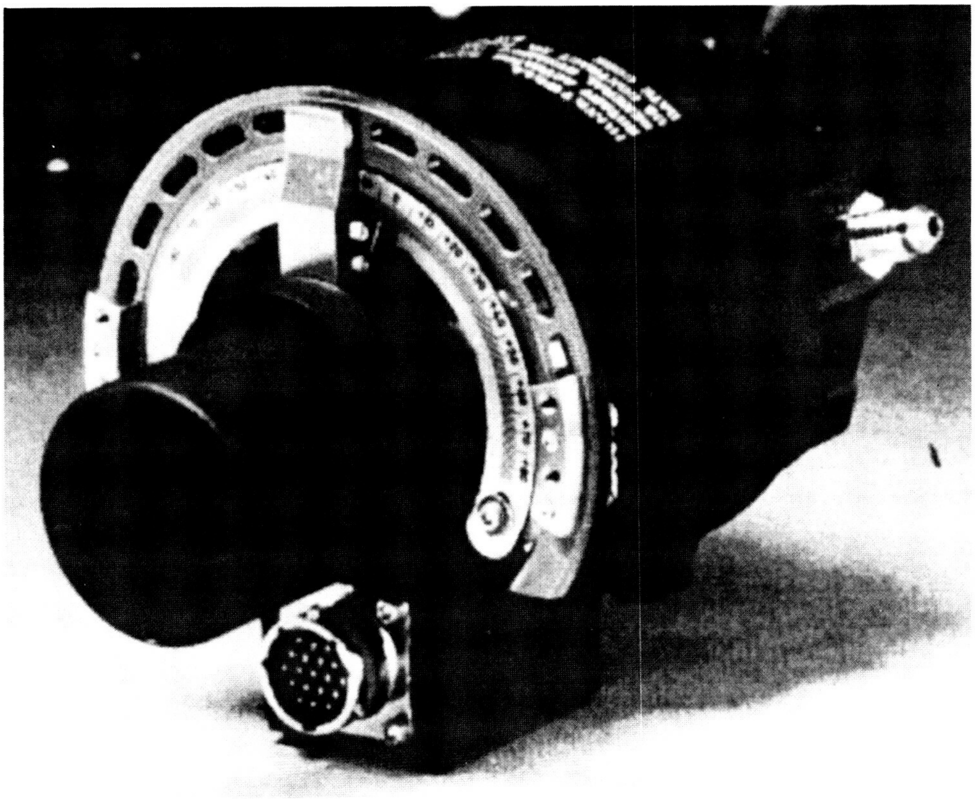

FIGURE 4. ROTARY ACTUATOR 2961041