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Miniature Rotary Actuator

R. A. Fink and R. C. Ellis*

Abstract

The trend toward smaller satellites has challenged component manufacturers to reduce the size, weight, and cost of their products while maintaining high performance. Both a new stepper motor and a new harmonic drive were developed to meet this need. The resulting actuator embodies small angle stepper technology usually reserved for larger units and incorporates an integral approach to harmonic drive design. By product simplifications, costs were significantly reduced over prior designs.

Introduction

Design and fabrication of a new miniature actuator presented a number of challenges. As the unit size is reduced, manufacturing tolerances must be tightened to maintain the same relative precision and performance that customers expect. A new product generally evolves from a fresh look at existing technology with improvements based on changing needs. Development must also consider that the customers for smaller satellites are insisting on lower cost. New concepts in design would be required to simplify the hardware while maintaining or improving quality. Both the motor and harmonic drive designs were analyzed with these goals.

This paper addresses the development of a new motor in the first section. The second section discusses the harmonic drive design and the third section reports the results of the complete actuator. There were a number of problems and lessons learned at each step of the development. Final optimization depended on the close cooperation of the motor and harmonic drive manufacturers.

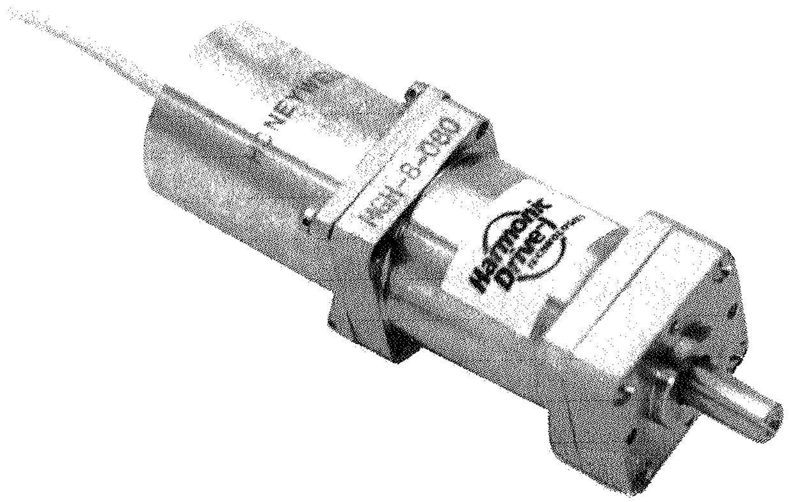

Figure 1

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* Honeywell Electro Components, Durham, NC

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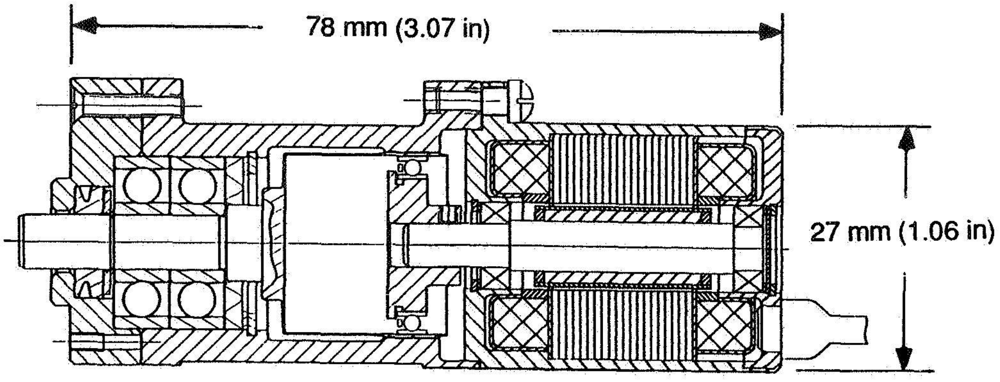

Figure 2

Stepper Motor

The motor design developed on this project combines a large number of poles (12) in a small size 11 package. This results in a smaller step angle (15 degrees), a higher step rate, and more torque than conventional permanent magnet stepper motors of the same size. The motor maintains the same inertia as 2 pole motors of the same size. The motor was also designed to have the same resistance as many previous 2-pole, 90-degree stepper designs used on numerous space programs, ensuring that the input power and thermal considerations remain unchanged. This motor technology has been used in a larger diameter for a 2 phase unipolar, 2-degree stepper to drive a two-axis antenna pointing mechanism for a commercial satellite.

Motor Test Results

The motors were tested for basic parameters; resistance, inductance, etc., then subjected to running tests. Table 1 summarizes the test data. Powered data is at 24 volts. The maximum start-stop rate was measured by slowly increasing the step rate until the unit would not consistently start and recording the highest rate it would always start. The maximum slew rate was measured by powering the motor and gradually increasing the step rate until the motor stopped. The highest rate that the unit would always run was recorded.

Table 1, Summary of Motor Test Data

Parameter	Expected	S/N 1	S/N 2
Winding Resistance (Ω)	72	71.3	73.1
Inductance (mH)	20	20.5	21.8
Max. Start-stop Rate (pps)	900	911, 988	1000, 956
Max. Slew Rate (pps)	2000	2100, 2082	2104, 2128
Rated Torque at 400 pps (mN•m)	10.6 (in-oz)	12.2	11.3
Stall Torque (mN•m)	14 (2 in-oz)	15.2	14
Detent Torque (mN•m)	3.5 (0.5 in-oz)	1.4 - 5.6	1.4 - 5.6
Drag Torque: coulomb (mN•m)	1.4 (0.2 in-oz)	2	0.7
viscous (mN•m/rad/s)	0.0014	0.001	0.0019
Weight (kg)	-	0.114 (4 oz)	0.114

The detent torque was measured by back driving the unexcited motor at two degrees per second through a rotary torque transducer and recording the torque on a strip chart. The drag torque was measured in a similar fashion except at five speeds from approximately 60 to 380 $^{rad}/_{s}$ (600 to 3600 RPM). The drag torque was separated into coulomb and viscous components using a simple linear regression.

Lessons Learned, Motor

The engineering model motors built on this project performed as expected except the detent torque showed significantly more variation over the 24 detent null positions than desired or expected as shown in Figure 3. This variation was originally attributed to distortion of the magnetic laminations due to the prototype nature of the hardware machining. The cause was, in fact, a design anomaly which caused most of these variations. A careful analysis of the magnetic circuit revealed the importance of using critical proportions between elements of the circuit. Once this fact was determined, we designed a two-degree, two-phase motor using the same principles developed on this project while being careful to maintain the proper proportions in the magnet circuit. Figure 4 shows how the detent torque variations were minimized on this 2 degree step angle design.

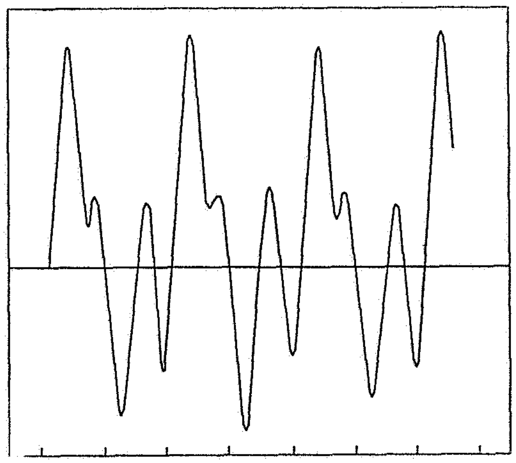

Figure 3

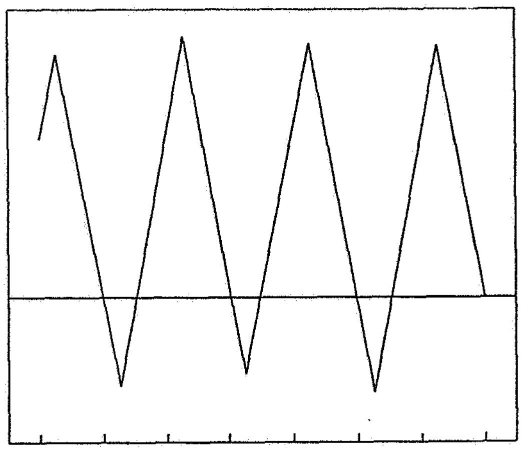

Figure 4

Harmonic Drive

Principle of Operation

As with all harmonic drives, the MGH 8 operates by rotating an elliptical-shaped wave generator within the flexspline causing a one tooth displacement with the circular spline. This displacement results in a high ratio between the input and output stages. The harmonic drive gearing in the MGH provides zero backlash, high positional accuracy, high torsional stiffness and a torque rating equal to conventional units twice its size.

Description of Design

The MGH 8 is a miniature gearhead with an integral harmonic drive having a 20 mm (0.8 inch) pitch diameter. It has an 80:1 ratio achieved by using very fine gear teeth (200 diametral pitch). The harmonic drive is designed to complement mechanical and performance characteristics of the stepper while incorporating new concepts. It has the same outer diameter and permits direct mounting of the motor. Several unique features improve reliability and structural simplicity. Materials and lubricants are spacecraft rated.

Integration of the harmonic drive components with the housing, bearings and shaft results in an elegant design with minimum parts count. The output shaft is integral to the flexspline. It is supported by two preloaded bearings (MPB SSR-1960 series) and includes an oil seal on the output shaft. The circular spline is machined integral with the gearhead housing, providing maximum miniaturization with minimum weight. The wave generator is mounted directly to the motor shaft, eliminating the need for the typical Oldham coupling.

Test Results, Harmonic Drive

Performance (see Table 2) maintained the high standards expected of a harmonic drive. The maximum torque rating comfortably exceeded the maximum motor stall torque, providing a 3:1 margin. Torsional stiffness, while high, was less than expected (see lessons learned). Positional accuracy was consistent with the reduced size.

Table 2

Torsional Stiffness (N•m/rad)		270 (2400 in-lb/rad)
Positional Accuracy (arc sec)		±185
Maximum output torque (N•m)		3.4 (30 in-lb)
Rated output torque (N•m)		1.6 (14 in-lb)
Shaft side load rating (N)	static	220 (50 lb)
	dynamic	67 (15 lb)

Lessons Learned, Harmonic Drive

Circular Spline

Although machining the circular spline directly into the housing has benefits in size and weight, it caused a deburring problem. Burrs created from shaping the teeth in the circular spline housing were difficult to remove. There were three reasons for the problem: a) the very small, 200 pitch gear teeth; b) the annealed 304L material; and c) the configuration of the gear blank.

Nothing could be done about the very small 200 pitch gear teeth required to produce the 80:1 ratio. The deburring problem was addressed by: a) redesigning the gear blank to provide more clearance for the shaper cutter at the end of the cutter stroke and b) changing the housing/circular spline material from 304L stainless steel to a more free machining 303 grade. This will require further investigation since 303 is not recommended for spacecraft applications.

Torsional Stiffness

The design goal for torsional stiffness was 360 N•m/rad (3200 in-lb/rad). The measured torsional stiffness of the MGH gearheads was 270 N•m/rad (2400 in-lb/rad). The original specification of 360 N•m/rad was calculated for the harmonic drive components and did not include the output shaft. The MGH is being offered as a complete gearhead with an integral output shaft. Therefore, the torsional stiffness value must include the shaft stiffness as well as the harmonic drive gear stiffness, and results in a lower value than the original design goal. This points out the need to calculate all contributors to stiffness even if they seem to be insignificant.

Integrated Actuator Assembly

Two stepper motors were assembled to harmonic drives and tested for critical performance characteristics. Motor testing showed good torque output at extremely high stepping rates. Computer analysis of the complete actuator showed that the maximum step rate would be reduced to about half of the rate of the motor alone. This was confirmed during test and was especially discouraging based on the high rate achieved for the motor (see lessons learned). Further development was indicated and is now in process.

The actuator design was tailored for several applications. It could be used as umbilical disconnect mechanisms and cover actuators as well as caging and deployment mechanisms. With the addition of power transfer capability (cable drum or slip rings), it could be used for a small solar array drive. Also under consideration is the use as antenna pointing mechanisms for small Low Earth Orbit satellites. The small step angle (0.1875°) may make this practical.

Cost projections of the new miniature actuator show that the design simplifications reduced cost to approximately half that of more conventional designs.

Test Results, Integrated Actuator

Two actuators were tested and exhibited similar performance except for a low speed torsional resonance in only one unit (see lessons learned). As expected, the stepping rate was reduced due to the inertia of the input wave generator, but the starting rate exceeded 500 pulses per second without pulse rate ramping. Output torque was exceptionally high for the unit size and weight. Detent torque is a function of the motor magnetic detent.

Table 3

Rated Torque (N•m @ 400 pps)	0.56 (5 in-lb)
Stall Torque (N•m minimum)	1.1 (10 in-lb)
Detent Torque (N•m minimum)	0.17 (1.5 in-lb)
Slew Speed (pulses per second)	1500
Step Angle (degrees)	0.1875
Weight (kg)	0.25 (8.5 oz)

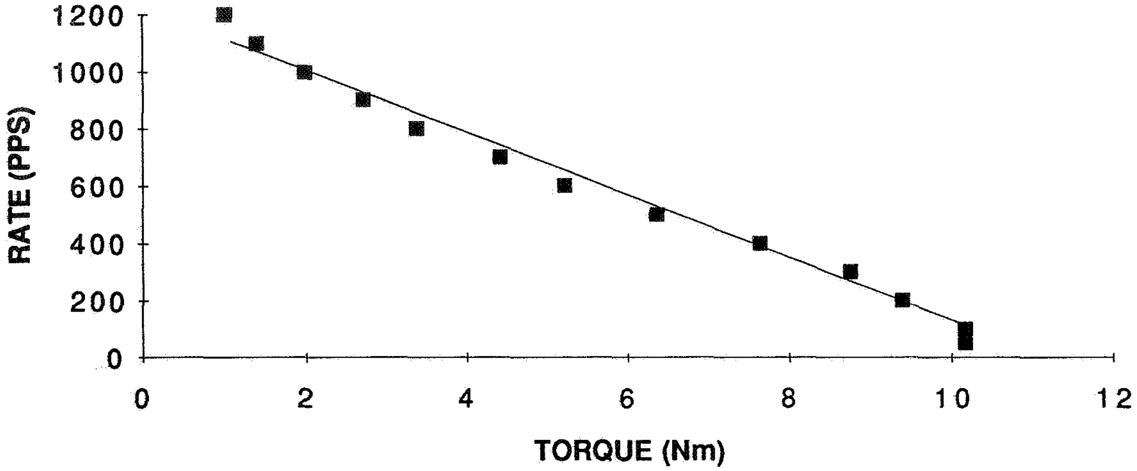

Figure 5

Lessons Learned, Integrated Actuator

Input inertia

The wave generator inertia limited the motor step rate to approximately half of the no-load motor rate. All stepper and servo motors are sensitive to load inertia. To decrease the inertia, the wage generator plug to which the wave generator bearing is assembled was changed from stainless steel to aluminum. This change halved the input inertia from 2.36 g•cm^2 (0.013 oz-in^2) to 1.21 g•cm^2 (0.0066 oz-in^2). The MGH gearhead was performance tested with both the steel and the aluminum plug. There were no measurable differences in the harmonic drive characteristics with the two different materials but high speed performance would be significantly improved. Further testing is scheduled and results should be available at the symposium.

Torsional resonance

One of the two development actuators exhibited a torsional resonance at step rates below 100 pps and performance was seriously degraded. Disassembly of the two harmonic drives revealed that the problem unit had a low torsional stiffness. This explained a low input drag and the resonance. The inertia of the test equipment load contributed to the resonance. It was realized that improved fitting tolerances would be required for production harmonic drives. This problem points out one of the major pitfalls in the use of stepper motors for driving inertia loads. They often become unstable at certain resonant frequencies. Any system that uses a stepper (with or without a harmonic drive) should be carefully analyzed for torsional stability over the full range of step rates expected.

Conclusions

While some design optimization is still needed, the development of this miniature, high-performance, low cost actuator would not have been possible without the mutual cooperation of the motor and harmonic drive manufacturers. There were no revolutionary design breakthroughs, just evolutionary adaptation of existing concepts to changing requirements.