ENHANCED POINTING GIMBAL MECHANISMS FOR NEXT GENERATION COMMUNICATION ANTENNAS

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ABSTRACT

This paper summarizes the design and the development of a family of high precision Enhanced Pointing Gimbal Assemblies (EPGA) specifically targeting the next generation of satellite communication antenna technologies.

The development and qualification of the first two EPGAs started some years ago. The purpose of this project has been to develop a gimbal based on a new rotary actuator technology achieving positioning performance superior to micro-stepping performance, to be used in highly accurate pointing and scanning mechanisms. The design also had to provide high stiffness and high load carrying capacity at the output stage.

The design of this new line of gimbals is based on a rotary actuator with a high gear reduction ratio and high load carrying capacity output stage.

Analysis of the latest missions, especially those for communication, earth observation and imaging, show that performance requirements for dual axis gimbals used for antenna pointing are becoming more and more demanding. Most recent Ka-band and future generation antenna technologies for smaller spot beams require finer resolutions of less than 0.003 degrees. Considerably larger solid core (~ 3.0 meter diameter) and expandable wire-mesh (~ 22 meter diameter) require higher load carrying capabilities and moment stiffness to sustain the launch and orbital maneuvering loads. The developed Enhanced Pointing Gimbal Assembly addresses those applications requiring small output step size, high precision pointing, and un-powered holding torque, which challenge the use of gimbals that use conventional rotary actuators.

1. INTRODUCTION

Moog Rotary Incremental Actuators are based on a basic geometry and configuration evolved more than three decades ago in response to the needs of the spaceflight community. Moog Chatsworth Operations (formerly Schaeffer Magnetics) developed a family of units based on the basic design, whose size progression reflects the size range of standard harmonic drive gear transmissions. The configuration and performance capabilities of these devices were found useful in many spaceflight applications, and they became a de facto standard in the industry.

The Moog Type 3 Rotary Actuator (RA) is used in Antenna Pointing Mechanisms (APM) on over 80 percent of commercial communication satellites. Moog Type 5 actuator, very similar in design and construction to the Type 3 RA is also very popular for antenna and payload pointing applications. The Enhanced Pointing Gimbal Actuator exhibits features similar to those of both the Type 3 and Type 5 actuators, with some added unique features tailored to address specifically the next generation of satellite communication antenna technologies.

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Output step sizes for the Type 3 and Type 5 actuators are 0.0094 degrees and 0.0075 degrees respectively. Even with the finest 1-degree stepper motor the output resolution can vary between 0.005 to 0.00625 degrees. To meet the new requirement of step sizes less than 0.003 degrees, a higher overall gear ratio is needed.

Figure1 depicts the Type5 Enhanced Pointing Actuator.

Figure 1 – Type5 EPGA Actuator

2. DESIGN DESCRIPTION

Since the speed reduction ratio of the harmonic drive transmission is limited to 200:1, additional speed reduction is needed to address the output step size. The decision was made to add a secondary pre-gear stage in the configuration of a small planetary gear pass in series with the motor and the harmonic drive. This approach has been exercised in a number of applications at Moog when an increased overall gear ratio was needed.

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Secondary planetary gearing has been added both before the harmonic drive and after the harmonic drive, at the output of Moog rotary actuators.

The addition of secondary planetary gearing before and after the harmonic drive transmission, apart from achieving higher gear ratio, offers unique performance characteristics. Pre-gear configuration maintains the torsional stiffness at the output and the zero-backlash characteristics inherent to harmonic drive design, while post-gear configuration increases the output torsional stiffness but introduces backlash inherent to conventional gear design.

A design trade study in which numerous factors were evaluated resulted in the decision to use an overall transmission ratio of 500:1. A design was evolved which consisted of a planetary gear pass of 5 to 1 ratio at the input to the harmonic drive with a gear transmission ratio of 100:1. This combination was chosen to satisfy the output torque without overloading the harmonic drive input torque and limiting the input revolutions for longer life. It should be noted that higher gear transmission result in higher revolutions on the motor input side limiting the life expectancy of the rotary actuator.

Conversely, actuators with low overall gear ratios may not provide sufficient mechanical advantage to meet expected torque requirements. Therefore, the selected gear ratio must be such to satisfy both life and performance requirements. The gear ratio selected as optimum for the EPGA actuator is 500:1, to limit the number of motor revolutions over the life of the actuator, and still provide adequate output torque with ample margin to meet the expected performance requirements.

The Enhanced Pointing Gimbal Assembly was developed in two versions to address two different applications.

A 4-phase standard 1.5 degree permanent magnet stepper motor was used in one type of EPGA resulting in an output step size of 0.003 degrees. A second version used a standard 3-phase 1.0 degree permanent magnet stepper motor resulting in an output step size of 0.002 degrees. These configurations represent the standard construction of many Moog-produced motors, including the Type3 and Type5. The design is efficient, and unlike the conventional hybrid type stepper motor, does not require an extremely small air-gap to achieve high torque and unpowered holding torque capability.

Conversely, if only a multi-stage planetary gear transmission were considered, at least four (4) stages would be needed. This would result in added length, mass and a higher parts count.

All of the electrical elements such as motors and position sensors are redundant.

Figure-2 – Type5 Enhanced Pointing Gimbal Assembly

Table 1 – Performance parameters for Type5 Enhanced Pointing Gimbal Actuators

Type 5 EPGA Specification	Data	
	3-Phase	4-Phase
Motor Step Angle (Degree)	1	1.5
Gear Transmission Ratio	500	500
Output Step Angle (Degree)	0.002	0.003
Nominal Running Torque (N.m)	107	45
Unpowered Holding Torque (N.m)	59	46
Nominal Torsional Stiffness (N.m/rad)	22,500	22,500
Nominal Moment Stiffness (N.m/rad)	112,000	112,000
Operating Temperature Range C	-50 to +105	-25 to +100
Outside Diameter (mm)	147	147
Overall Length (mm)	137	137
Mass (Kg)	2.7	2.7
Power Consumption (watts)	<10	<14
Electrical Redundancy	Yes	Yes
Lubrication	BRAY815Z	Pennzane 2000

3. TYPE5 EPGA QUALIFICATION AND LIFE TESTING

Both design configurations were exposed to completely different qualification and life testing profile for the following reasons:

1. Each configuration addressed different bus voltage and motor driver schemes.
2. Lubrication used were different to support temperature extremes.

3. Life profile addressed completely different antenna pointing duty cycles.

3.1 Thermal Cycling

The qualification and life testing environments included variations in Temperature (-60 to 115°C non-operating and - 50 to 105°C operating for 3-Phase design and (-42 to 98°C non-operating and - 25 to 85°C operating for 4-Phase design) during thermally controlled space vacuum simulation

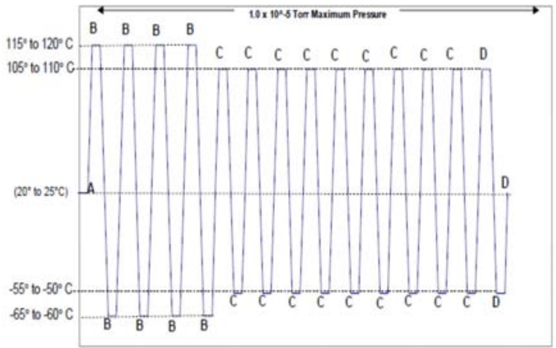

Figure 3 – Temperature Cycling Profile for the 3-Phase design configuration

3.2 Pressure

Pressure varied from ambient to $1x10^{-5}$Torr. vacuum

3.3 Sine vibration

The qualification units were exposed to a maximum 26g sinusoidal vibration with a sweep rate of 2 octaves/min from 5 to 100 Hz frequency range in all three (3) orthogonal axes.

3.4 Random Vibration

The qualification units were exposed to a 27 GRMS random vibration spectrum from 20 to 2000 Hz frequency range for 180 seconds per axis in all three (3) orthogonal axes.

Stiffness and Shock testing was performed at the dual axis gimbal level with a pre and post shock performance characterization tests. The following shock spectrum was applied to the EPGA. Unit passed the post shock performance tests.

3.5 Shock

Three applications of 900 g shock loads from 2000 to 10,000 Hz applied to three orthogonal axes. Shock loads were ramped from 14 g at 100 Hz to 100g at 500 Hz and 425g at 1000g to finally climbing to 900g at 2000 Hz

4. TYPE 6 EPGA DEVELOPMENT

After the successful qualification and life testing of Type5 EPGA units, at a request of a customer Moog started the development of a Type6 EPGA. The Type 6 EPGA is a two axis articulating mechanism that is configured into an "Elevation over Azimuth" gimbal formation. Both the elevation and azimuth actuators of the gimbal are identical to each other with the only exception being the adjustable stop location that is application specific and limits the angular travel of the elevation and azimuth actuators as required. The elevation and azimuth axes are electromechanical rotary incremental actuators designed to be actuated by stepper motors. To improve and address specific performance applications, these stepper motors are coupled to a planetary gear drive and a harmonic Drive (HD) gear transmission in series. Combination of planetary and HD gear reduction systems provide a higher gear ratio that cannot be achieved by either of these gear systems independently. In addition to this mechanical advantage which is manifested as a significant torque increase at the output of the actuator, the positioning of the gear train so that the HD is directly the output of the actuator also allows the performance characteristics of the HD such as "zero backlash" and "high torsional stiffness" to be directly transferred into the actuator. A unique feature of the design as opposed to other Moog manufactured actuators with HD gear transmission is the mounting configuration of the HD. The Type 6 EPGA is configured such that the circular-spline of the Harmonic Drive is the output flange of the actuator. The advantage of this configuration is that the bolted interfaces which are susceptible to slippage under high torsional loads are eliminated.

To complement the high accuracy and zero backlash attributes of the EPGA, a fine and coarse Moog QuieSense™ [1] potentiometers are provided at the back of the actuator. The wipers for the fine potentiometer are attached to the rotor of the stepper motor and the wipers of the coarse potentiometer are attached to the output of the actuator. The fine and coarse potentiometers function in tandem to provide accurate positioning information. The coarse potentiometer provides the information that could be used to establish the number of complete fine potentiometer revolutions to reach a specific location. Once this position is established, the fine potentiometer will then indicate where the position of the actuator is within a 360 degree track of the potentiometer. Although this is a typical description of how fine and coarse potentiometers combine to provide accurate position indication, the Type 6 EPGA Moog QuieSense™ potentiometers are designed to provide high accuracy telemetry information in slightly different manor which is out of the scope of this paper

The EPGA actuators are also equipped with redundant heaters and thermistors for temperature control and indication. Adjustable stationary stops are provided at the mounting flange of the actuators. Joining the elevation and azimuth actuators via a precision machined one piece aluminum bracket produces the "Elevation over Azimuth" gimbal configuration.

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The Type 6 EPGA comes in two configurations; 505:1 and 805:1 gear transmission ratios resulting in 0.002 and 0.0012 degrees of output step size.

Figure 4 shows the fully assembled Type 6 EPGA actuator unit. The qualification EPGA unit is currently under fabrication. The Dual Axis Type6 EPGA is expected to be ready for qualification and life testing by October 2013. Qualification and extended life testing will conclude by March 2014. The Type6 EPGA is depicted in Figure 5.

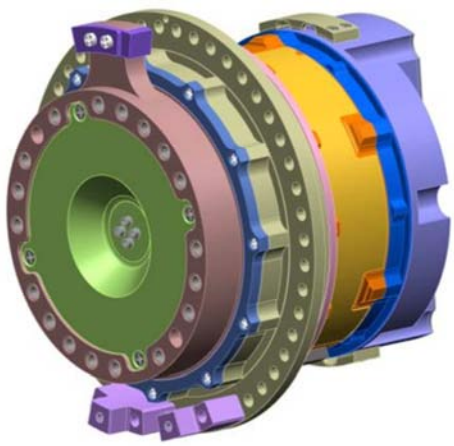

Figure-4, Type 6 EPGA Actuator

The performance specification for the Type6 EPGA actuator is summarized in Table 2.

Table 2 – Performance parameters for Type6 Enhanced Pointing Gimbal Actuators

Type6 EPGA Actuator Specification	Data	
	505:1	805:1
Motor Step Angle (Degree)	1	1
Gear Transmission Ratio	505	805
Output Step Angle (Degree)	0.002	0.0012
Minimum Running Torque at 24 V @ +105C (N.m)	79	126
Maximum Running Torque at 29.5 V @ -50C (N.m)	293	466
Unpowered Holding Torque (N.m)	124	195
Nominal Torsional Stiffness (N.m/rad)	101,500	101,500
Nominal Moment Stiffness (N.m/rad)	240,000	240,000
Operating Temperature Range C	-50 to +105	-25 to +100
Outside Diameter (mm)	158	158
Overall Length (mm)	137	137
Mass (Kg)	3.7	3.7
Power Consumption (watts)	<10	<10
Electrical Redundancy	Yes	Yes
Lubrication	BRAY815Z	

5. TYPE 3 EPGA DEVELOPMENT

To complete the Enhanced Pointing Gimbal Actuator family of products a design study was performed on the viability of producing similar concept actuator with a Moog standard Type3 size. The study indicated that this is feasible and a third variety of the EPGA line has been designed to have the identical mechanical interfaces of a Moog Type 3 Rotary actuator line (Figure 6). This is a “drop-in replacement” to accommodate customers who are currently using the Moog Type3 RA for their antenna pointing mechanisms. The design offers both a 3-phase and 4-phase unipolar (2-phase bi-polar) stepper motor options. It provides step resolutions of 0.001 to 0.003 degrees, a minimum unpowered holding capability of 58 Nm and a minimum moment stiffness of 112,000 N.m/Rad.

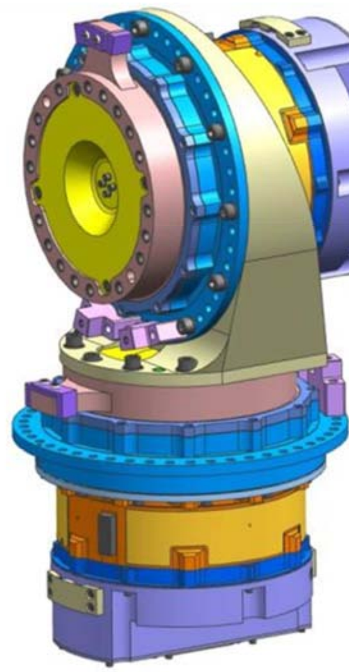

Figure-5 – Type6 Enhanced Pointing Gimbal Assembly

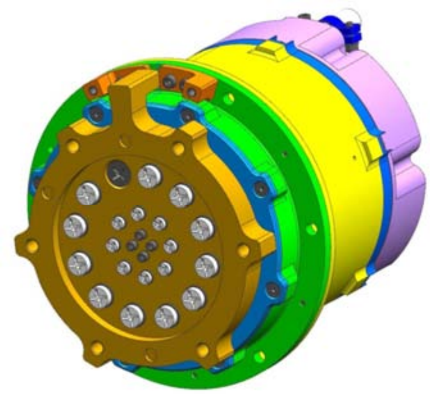

Figure-6 – Type3 Enhanced Pointing Gimbal Actuator

The performance specification for the Type3 EPGA actuator is summarized in Table 3.

Table 3 – Performance parameters for Type3 Enhanced Pointing Gimbal Actuators

Type3 EPGA Actuator Description	Data	
	Option 1	Option 2
Motor Step Angle (Degree)	1	1
Gear Transmission Ratio	500	1000
Output Step Angle (Degree)	0.002	0.001
Nominal Running Torque (N.m)	107	200
Unpowered Holding Torque (N.m)	58	110
Nominal Torsional Stiffness (N.m/rad)	22500	22500
Nominal Moment Stiffness (N.m/rad)	45200	45200
Operating Temperature Range C	-45 to +95	-45 to +95
Outside Diameter (mm)	122	122
Overall Length (mm)	127	127
Mass (Kg)	2.6	2.6
Power Consumption (watts)	< 10	< 10
Electrical Redundancy	Yes	Yes

6. CONCLUSION

The design of a family of high precision Enhanced Pointing Gimbal Assemblies (EPGA) specifically targeting the next generation of satellite communication antenna technologies is based on heritage hardware components integrated into a compact package.

Modularity of the design and the possibility of selecting different motor step angles and harmonic drive gear ratios, make variations optimized for different applications.

Finally, the Type5 EPGA has been fully qualified and life tested for operations at ambient and at extreme hot and cold vacuum environments to assess its capabilities. The Type6 EPGA will complete its qualification and life testing by the first quarter of 2014. It was determined that the Qualified EPGA units meet all the strict performance requirements with acceptable margins.

7 REFERENCES

1. "Development of a Noise-Free Position Encoding Device for Spaceflight Use", Ruben Nalbandian & Stefan Berres (2011) Proceedings of 14th ESMATS Conference, Constance, Germany,pp 169-175