Development of the Upgraded DC Brush Gearmotor

FOR SPACEBUS PLATFORMS

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Management Summary

The obsolescence of materials and processes used in the manufacture of traditional DC brush gearmotors has necessitated the development of an upgraded DC brush gearmotor (UBGM). The current traditional DC brush gearmotor (BGM) design was evaluated using the Six-Sigma process to identify potential design and production process improvements. The development effort resulted in a qualified UBGM design that improved manufacturability and reduced production costs. Using Six-Sigma processes and incorporating lessons learned during the development process also improved motor performance for the UBGM, making it a more viable option for future use as a deployment mechanism in space flight applications.

Introduction

DC brush gearmotors have been used for several years in various spaceflight applications because of their many favorable design features. They are extremely efficient at converting electrical energy into mechanical energy, using only simple control electronics. Existing, qualified DC brush gearmotors for space flight applications, however, use some obsolete materials and processes in their design and construc-

Figure 1—Existing brush gearmotor (BGM).

tion. The intent of this presentation is to review the existing BGM design, using the Six-Sigma process to identify potential design improvements and to select replacements for the obsolete materials and processes. This paper documents the development and qualification of a UBGM for use as a solar array deployment mechanism on the Spacebus satellite platform that maximizes motor performance, lowers overall drag and optimizes manufacturability.

The BGM has to operate in hostile environmental conditions during test and flight. The proper selection of materials is critical. Factors that must be considered include:

- Operate in ambient air, up to 55% relative humidity
- Survive random vibration (32.3 G rms)
- Survive in vacuum (1.0 x 10^{-5} torr)
- Operate in vacuum (1.0 x 10^{-5} torr) from –50° C to +80° C
- Survive in vacuum (1.0 x 10^{-5} torr) from –50° C to +125° C

Background

The qualified BGM (Fig. 1) consisted of a DC brush motor and a multi-stage planetary geartrain. The design used brush material that has since been discontinued and other obsolete materials and employed non-forgiving process-driven steps that resulted in high manufacturing costs. The redesign addresses materials and processes, manufacturing changes and test tooling improvements that are necessary for future successful production of the new, upgraded DC brush gearmotors.

Purpose of redesign:

- Enhanced producibility
- Improved functional performance characteristics
- Reduced delivery schedules
- Increased robustness

Development

The existing BGM design was analyzed and a 3-D CAD model was created in Unigraphics. Prior failures and manufacturing problems were reviewed for areas of improvement. A Six-Sigma product assurance process was conducted. Trade studies were performed on major assemblies and a detailed tolerance analysis was completed to identify potential interferences.

A Six-Sigma process improvement team was established. Process walkthroughs were completed on six assemblies and three piece parts from the existing manufacturing and build cycles. Personnel were interviewed and fabrication, assembly and test processes of the existing BGM units were observed. Forty eight items were identified for improvement. Trade studies were initiated on all sub-assemblies and major components. Design and manufacturing process changes were completed to address all identified issues. The following major areas of potential improvement were identified:

Process improvements:

- Commutator soldering and inspection

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- Armature paint integrity
- Armature insulation

Performance improvements:
- Optimized motor speed and motor torque
- Predictable gearhead drag

A gearhead trade study was completed to develop a consistently producible design with predictable gear drag over the required temperature range. Review of the existing gearhead design and a detailed tolerance analysis showed: a potential interference at cold temperatures; high drag in the first- and second-stage bushings; a material combination prone to galling (same gear material used on mating gear teeth); and a high sensitivity to gear center distance shift. The following trade study criteria were selected for gearhead design improvement:
- Provide similar gear ratio
- Non-binding operation at extreme temperatures
- Manageable internal loss
- Robust design
- Non-galling material combinations

Three different gearhead concepts were selected for design and testing:
1. Completely redesigned gearhead
2. Harmonic drive gearhead
3. Modified existing gearhead using radial ball bearings

Engineering models of each concept were fabricated and tested. The redesigned gearhead (concept 1) had higher and inconsistent drag over the required temperature range; the harmonic drive gearhead (concept 2) exhibited significantly higher drag at ambient temperatures, so no further testing was required; the modified gearhead using radial ball bearings (concept 3) was ultimately selected, based on its low and consistent drag over the required temperature range. Table 1 lists gearhead drag of engineering models over the required temperature range. The modified gearhead does not exhibit interference over the required temperature range, has reduced drag in the first and second stages, has no galling material combinations and uses a one-piece ring gear to minimize sensitivity to gear center distance shift.

A new brush material was identified and selected at the conclusion of the motor trade study. A detailed review of

Table 1—Gear Head Drag

		Gear Drag @ 450 RPM (N-cm)			Gear Drag @ 450 RPM (in-oz)		
	Description	-50°C	+23°C	+80°C	-50°C	+23°C	+80°C
SN042	Existing Design Drive	0.22	0.06	0.07	0.31	0.09	0.10
Option #1	Redesign Drive	1.78	0.60	0.44	2.52	0.85	0.63
Option #2	Harmonic Drive		3.53			5.00	
Option #3	Radial Bearing Drive	0.16	0.01	0.02	0.23	0.02	0.03

Table 2—Brush Performance

	Motor Torque	Brush							Commulator
Brush Material	SN0042 N-cm (in-oz)	Wear in Atmosphere	Wear In Vacuum	Drag N-cm (in-oz)	Debris	Smearing	Resistance (Ω)	Yield	Wear
1	1.77 (2.50)	Good	Good	0.29 (0.41)	Moderate	None	0.13	Good	Excellent
2	1.20 (1.70)	N/A	N/A	0.23 (0.33)	N/A	N/A	0.21	Good	N/A
3	0.85 (1.20)	N/A	N/A	0.25 (0.35)	N/A	N/A	0.20	Good	N/A
4	1.77 (2.50)	Good	Poor	0.41 (0.58)	Moderate	None	0.16	Excellent	Excellent
Existing	1.77 (2.50)	Excellent	Excellent	0.46 (0.65)	Light	Light	0.56	Good	Good

Table 3—Motor Performance

	Motor Torque (N-cm / in-oz)				
Unit	Brush Material #1	Brush Material #2	Brush Material #3	Brush Material #4	Existing
SN 0042	1.8 (2.5)	1.2 (1.7)	0.85 (1.2)	1.8 (2.5)	1.6 (2.2)
EM 0001	2.4 (3.4)	N/A	N/A	2.3 (3.3)	1.9 (2.7)

Figure 2—Upgraded brush gearmotor (UBGM).

the existing motor design revealed inefficient processes, high brush drag and use of discontinued brush material.

The brush assembly consists of a carbon-composite brush, shunt wire, cap and spring. Eight different brush materials were considered and four were selected for testing. All brushes were tested for motor performance, resistance, drag, spring force, brush wear, commutator wear, smearing, debris and manufacturing yield. Brush material options 2 and 3 were eliminated due to low motor torque. Brush material option 1 was selected due to poor performance of option 4 in a vacuum. Table 2 lists development brush performance. The selected brush material is softer than the existing brush material, resulting in higher motor torque, lower brush drag and less commutator wear.

The motor trade study considered all assemblies and machined parts. The producibility of the existing motor is poor, due to the need for frequent rework resulting in high production costs. Stack fabrication, coating and attachment methodology were upgraded to current Moog procedures. All uncontrollable and unnecessary processes were replaced or eliminated. For instance, existing BGM commutators are machined after final armature assembly, putting the completed armature at risk. UBGM commutator processing was moved to the piece part level to lower the risk to hardware. The soldering process was updated to the current standard. Table 3 shows increased motor torque with new brush materials, design and manufacturing changes.

The overall development of the upgraded brush gearmotor was successful. All issues discovered during the Six-Sigma process were addressed. After development was completed, a qualification unit (Fig. 2) was fabricated to specification, using production processes and tooling. The unit was subjected to qualification testing that included vibration, thermal-vacuum exposure and life tests. The qualification unit successfully passed all qualification and life tests with no findings.

Lessons Learned

While the upgraded brush motor development and qualification were successful, the methodology in some areas needs improvement. The following documents the major lessons learned during development and qualification:

Understand derived requirements. A firm understanding of the requirements (actual and derived) is needed prior to development. At the onset of the development process, the gearhead bushings were identified as a cause of BGM performance problems. A total redesign of the gearhead was started, with heritage design practices, processes and software utilized in the new gearhead. Gear design parameters were optimized to allow for greater allowable tolerances and used compatible material combinations to reduce galling and thermal expansion issues. Optimization of the gearhead for producibility adversely affected performance, however.

Since the BGM motor torque output is relatively low, it

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Table 4—Brush Wear

				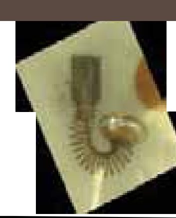
New Brush	A1	A2	B1	B2
Percent Reduction	~14%	~14%	~14%	~17%

Table 5—UBGM vs BGM Performance Comparison

		UBGM						BGM					
		-50°C		+23°C		+80°C		-50°C		+23°C		+80°C	
Test Description	Units	Max	Mn	Max	Mn	Max	Mn	Max	Mn	Max	Mn	Max	Mn
Drag torque only (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.15 (0.21)		0.06 (0.09)		0.04 (0.05)		0.15 (0.21)		0.06 (0.09)		0.04 (0.05)	
Drag torque tooling only (torque to start)	N-cm (in-oz)	0.18 (0.25)		0.06 (0.08)		0.05 (0.07)		0.18 (0.25)		0.06 (0.08)		0.05 (0.07)	
Drag torque gearbox (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.31 (0.44)		0.08 (0.11)		0.06 (0.08)		0.37 (0.52)		0.13 (0.18)		0.11 (0.05)	
Drag torque gearbox (torque to start)	N-cm (in-oz)	0.18 (0.26)		0.06 (0.08)		0.04 (0.06)		0.18 (0.26)		0.07 (0.10)		0.06 (0.08)	
Tool drag removed													
Drag torque gearbox (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.16 (0.23)		0.01 (0.02)		0.02 (0.03)		0.22 (0.31)		0.06 (0.09)		0.07 (0.10)	
Drag torque gearbox (torque to start)	N-cm (in-oz)	0.01 (0.02)		0.00 (0.00)		0.00 (0.00)		0.01 (0.02)		0.01 (0.02)		0.07 (0.01)	
		UBGM						BGM					
		-50°C		+23°C		+80°C		-50°C		+23°C		+80°C	
Test Description	Units	Max	Mn	Max	Mn	Max	Mn	Max	Mn	Max	Mn	Max	Mn
Drag torque motor (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.99 (1.40)		0.99 (1.40)		0.99 (1.40)		0.85 (1.20)		0.81 (1.15)		0.78 (1.10)	
Drag torque gearbox (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.16 (0.23)		0.01 (0.02)		0.02 (0.03)		0.22 (0.31)		0.06 (0.09)		0.07 (0.10)	
Drag torque motor (torque to start)	N-cm (in-oz)	1.31 (1.85)		1.31 (1.85)		1.31 (1.85)		2.8 (4.0)		2.8 (4.0)		2.8 (4.0)	
Drag torque gearbox (torque to start)	N-cm (in-oz)	0.01 (0.2)		0.00 (0.00)		0.00 (0.00)		0.01 (0.02)		0.01 (0.02)		0.007 (0.01)	
No load speed (motor with 6.0V)	rpm	588	571	549	505	572	563	440	405	480	455	515	470
No load speed (motor with 6.0V)	amps	0.081	0.080	0.077	0.072	0.065	0.062	0.100	0.095	0.098	0.095	0.078	0.075
Time to rotate 90 degrees (motor and gearbox with 6.6V)	sec	78.5	75.5	82	76.75	78.75	74.25	68.00	65.00			74.00	72.00
No load speed (motor and gearbox with 6.6V)	rpm	0.19	0.20	0.18	0.20	0.19	0.20	0.01	0.231			0.203	0.208
No load speed (motor and gearbox with 6.6V)	amps	0.101	0.099	0.093	0.084	0.084	0.078	0.01	0.070			0.086	0.083
Stall torque (motor with 6.0)	N-cm (in-oz)	3.2 (4.5)	3.2 (4.5)	2.4 (3.4)	2.4 (3.3)	2.0 (2.9)	1.9 (2.7)	2.1 (3.0)	1.6 (2.2)	1.2 (1.7)	0.76 (1.1)	1.1 (1.6)	0.78 (1.1)
Stall torque (motor and gearbox with 6.6V)	N-cm (in-oz)	48.0 47.5	47.5 (420)	50.6 (488)	49.5 (438)	48.0 (425)	47.5 (420)	36.2 (320)	33.9 (300)	29.0 (257)	28.8 (255)	33.1 (293)	29.9 (265)

Tested at 6.0 V

is sensitive to drag torque. Valuable time was spent on developing a new gearhead that had a gear drag greater than the motor could produce. If the BGM gear drag data had been available, it would have been realized that there was little chance to design a new gearhead with significantly lower drag.

Understand test capabilities. At the start of development it was determined we would test all gearheads before they were integrated into the BGM. It was assumed we would use our standard test setup, tooling and test equipment. But during initial gear drag testing it was discovered that minor misalignment caused major shifts in the drag torque measurement. Thermal expansion of the tooling was enough to double or triple drag torque measurements. In response, a standardized process was developed to consistently adjust the alignment before each test.

Verify performance at every environment. During testing it was observed that brush drag and wear were different in vacuum than at ambient pressure. The leading brush material was eliminated after vacuum testing. Almost no wear was observed during ambient and initial vacuum testing, but during extended vacuum testing the brush was completely worn away.

Work with suppliers to understand procured part requirements. One brush manufacturer's brush shunt wire broke significantly more than the others. The brush shunt attachment had to be redesigned to address yield issues. The initial design used an eyelet to keep the solder from wicking down the shunt wire (their internal requirement). The eyelet damaged the wire strands, causing them to fail. The eyelet was removed and replaced with a braided shunt wire. The redesigned brushes were installed into the engineering model for functional and vibration testing. The redesigned brushes successfully completed testing without any broken shunt wires.

The issues involved with the "lessons learned" were not catastrophic, but each one of them could have had serious consequences. The upgraded brush gearmotor was successful because these issues were identified and addressed soon enough to enable meeting program schedule dates.

After development was completed, a qualification unit was fabricated to per production specification using production processes and tooling. The unit was subjected to qualification testing that included vibration, thermal vacuum exposures and life tests. The qualification unit successfully passed all qualification and life tests with no findings. After qualification and life testing, the unit was disassembled and cleaned. All parts were inspected and showed minimal wear and no signs of damage.

The new brush material meets all design requirements, and brush wear was consistent with wear observed during engineering testing. An estimated loss of 17% of usable brush material was observed.

Successful qualification was a direct result of the trade study development. The Six-Sigma process and trade study identified the driving requirements. DC brush gearmotor performance was improved, resulting in an approximately 11 N-m (100 in-lb) torque increase at the output. The upgraded gearhead assembly is a robust design with lower drag, non-binding operation at all temperatures and non-galling material combinations. The risk of damage to hardware during assembly was lowered due to design simplification. The new qualified DC brush gearmotor is a robust design capable of handling all environmental conditions with consistent, predictable performance.