# Development of the Upgraded DC Brush Gear Motor for Spacebus Platforms

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## Abstract

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

## Introduction

DC brush gear motors 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 gear motors for space flight applications however, use some obsolete materials and processes in their design and construction. The intent of this development was 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:

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

## Background

The qualified BGM shown in Figure 1 consisted of a DC brush motor and a multi-stage planetary gear train. The design used brush material that was since discontinued, some 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 gear motors.

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Purpose of Redesign:

1. Enhanced producibility
2. Improved functional performance characteristics
3. Reduced delivery schedules
4. Increased robustness


**Figure 1. Existing BGM**

## Development

The existing BGM design was analyzed and a 3D 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 walk-throughs 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 for improvement were identified. Trade studies were initiated on all subassemblies 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
  - Armature paint integrity
  - Armature insulation
- Performance Improvements
  - Optimized motor speed and motor torque
  - Predictable gear head drag

A gear head trade study was completed to develop a consistently producible design with predictable gear drag over the required temperature range. Review of the existing gear head design and a detailed tolerance analysis showed a potential interference at cold temperatures, high drag in the first & 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 gear head design improvement:

Provide similar gear ratio
Non-binding operation at extreme temperatures
Manageable internal loss
Robust design
Non-galling material combinations

Three different gear head concepts were selected for design and testing: a completely redesigned gear head (option #1), a harmonic drive gear head (option #2), and a modified existing gear head using radial ball bearings (option #3). Engineering models of all options were fabricated and tested. The redesigned gear head had higher and inconsistent drag over the required temperature range. The harmonic drive gear head exhibited significantly higher drag at ambient temperatures, so no further testing was required. The modified gear head using radial ball bearings (option #3) was ultimately selected based on its low and consistent drag over the required temperature range. Table 1 lists gear head drag of engineering models over the required temperature range. The modified gear head 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.

**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 | 0.22 | 0.06 | 0.07 | 0.31 | 0.09 | 0.10 |
| Option #1 | Redesign | 1.78 | 0.60 | 0.44 | 2.52 | 0.85 | 0.63 |
| Option #2 | Harmonic drive | | 3.53 | | | 5.00 | |
| Option #3 | Radial Bearing | 0.16 | 0.01 | 0.02 | 0.23 | 0.02 | 0.03 |

A new brush material was identified and selected at the conclusion of the motor trade study. Detailed review of 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 option #2 and #3 were eliminated due to low motor torque. Brush material option #1 was selected due to poor performance of option #4 in 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.

**Table 1. Brush Performance**

| | Motor Torque | Brush | | | | | | | Commutator |
|---|---|---|---|---|---|---|---|---|---|
| Brush Material | SN 0042 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 |

The motor trade study considered all assemblies and machined parts. The producibility of 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 and design and manufacturing changes.

**Table 2 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) |

The overall development of the upgraded brush gear motor was successful. All issues discovered during the Six-Sigma process were addressed. After development was completed a qualification unit shown in Figure 2 was fabricated to production paper work, using production processes and tooling. The unit was subjected to qualification testing which included vibration, thermal vacuum exposures and life tests. The qualification unit successfully passed all qualification and life tests with no findings.


**Figure 2. UBGM**

## Lessons Learned

While the upgraded brush motor development and qualification was successful, but the methodology in some areas could have been improved. The following paragraphs document the major lessons learned during development and qualification.

<u>Understand derived requirements</u>

A firm understanding of the requirements (actual and derived) is needed prior to development. At the onset of the development process, the gear head bushings were identified as a cause of BGM performance problems. A total redesign of the gear head was started, with heritage design practices, processes, and software utilized in the new gear head. 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 gear head for producibility adversely affected performance, however.

Since the BGM motor torque output is relatively low, it is sensitive to drag torque. Valuable time was spent on developing a new gear head 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 gear head with significantly lower drag.

<u>Understand test capabilities</u>

At the start of development it was determined we would test all gear heads before they were integrated into the BGM. It was assumed we would use our standard test setup, tooling and test equipment. 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. A standardized process was developed to consistently adjust the alignment before each test.

<u>Verify performance at every environment</u>

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.

<u>Work with suppliers to understand procured part requirements</u>

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 a braided shunt wire was used. 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 gear motor was successful because the issues were handled early enough to meet program schedule dates.

## Summary and Discussion

After development was completed a qualification unit was fabricated to production paper work, using production processes and tooling. The unit was subjected to qualification testing which 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.

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

**Table 3. Brush Wear**

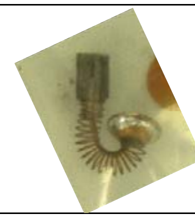
|  |  |  |  |  |
|---|---|---|---|---|
| New Brush | A1 | A2 | B1 | B2 |
| Percent Reduction | ~14% | ~14% | ~14% | ~17% |

**Table 4. UBGM vs BGM Performance Comparison**

| | | UBGM | | | | | | BGM | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -50°C | | +23°C | | +80°C | | -50°C | | +23°C | | +80°C | |
| Test Description | Units | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min |
| Drag torque Tooling 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 (0.15) | |
| 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) | | 0.007 (0.01) | |

| | | UBGM | | | | | | BGM | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -50°C | | +23°C | | +80°C | | -50°C | | +23°C | | +80°C | |
| Test Description | Units | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min |
| 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 (0.02) | | 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 6.0 V) | rpm | 588 | 571 | 549 | 505 | 572 | 563 | 440 | 405 | 480 | 455 | 515 | 470 |
| No load current (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 6.6 V) | 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 6.6 V) | rpm | 0.19 | 0.20 | 0.18 | 0.20 | 0.19 | 0.20 | 0.221 | 0.231 | | | 0.203 | 0.208 |
| No load current (Motor and GearBox with 6.6 V) | amps | 0.101 | 0.099 | 0.093 | 0.084 | 0.084 | 0.078 | 0.080 | 0.070 | | | 0.086 | 0.083 |
| Stall Torque (Motor with 6.0 V) | N-cm (in-oz) | 3.2 (4.5) | 3.2 (4.5) | 2.4 (3.4) | 2.3 (3.3) | 2.0 (2.9) | 1.9 (2.7) | 2.1 (3.0) | 1.6 (2.2) | 1.2 (1.7) | 0.78 (1.1) | 1.1 (1.6) | 0.78 (1.1) |
| Stall Torque (Motor and GearBox with 6.6 V) | N-m (in-lb) | 48.0 (425) | 47.5 (420) | 50.6 (448) | 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 (shaded cells: BGM +23°C stall torque, motor and gearbox)

Successful qualification was a direct result of the trade study development. The Six-Sigma process and trade study identified the driving requirements. DC brush gear motor performance was improved resulting in approximately 11 N-m (100 in-lb) torque increase at the output. The upgraded gear head 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 gear motor is a robust design capable of handling all environmental conditions with consistent predictable performance.