SEALED BRUSH GEAR MOTOR (SBGM) - QUALIFICATION TESTING WITH FOCUS ON RANDOM VIBRATION TESTING

M. Zimmermann [1], M. Herrscher [1], R. Schwarz [1], M. Schmalbach [1], B. Bonduelle [2], G. Migliorero [3]

[1] RUAG Space, RUAG Schweiz AG, Schaffhauserstrasse 580, 8052 Zürich, Switzerland, Email: michael.zimmermann@ruag.com, marc.herrscher@ruag.com, ralf.schwarz@ruag.com , matthias.schmalbach@ruag.com

[2] Soterem, ZI de Vic-BP 42297, 5 rue de la Technique, F-31322 Castanet-Tolosan Cedex, France, Email:bruno.donduelle@soterem.fr

[3] ESTEC, P.O. Box 299. 2200 AG Noordwijk, The Netherlands, Email: gerard.migliorero@esa.int

ABSTRACT

During the axial direction random vibration test, in the frame of the qualification test campaign of the SBGM mechanism, a frequency shift has been observed indicating a stiffening effect.
This observation led to a detailed investigation firstly by analysis and secondly, to confirm the root cause, by inspection while disassembling the mechanism down to its parts level after completion of the qualification test campaign. As outcome of the findings made during this investigation, improvements have been defined for an SBGM design evolution.
This paper describes the investigation process, the findings as well as the defined way forward.

1 INTRODUCTION

When operated under space vacuum, brushed DC motors commonly show problematic behaviour with regard to reliability due to brush issues in the commutator. The presented actuator solves issues like the generation of debris from the brushes, arcing, and an unstable and high brush friction by the use of a hermetically sealed housing that contains its own atmosphere. Due to the low leak rate, the internal pressure is kept at a sufficient level for more than 50 years in orbit. Torque is transferred from the motor to the gear head by means of a magnetic hysteresis coupler. A special characteristic of this coupler is its ability to not only limit the transferred torque but also to maintain the adjusted torque during slippage within the coupler.

Design highlights:

- Reliable behaviour of the brushes running in air
- No need for complex electronics, as commutation is performed mechanically
- Hysteresis coupler acts as a torque limiter
- High gear efficiency through thorough use of ball bearings
- Insensitive to vibration and shock due to (soft) preloaded gear

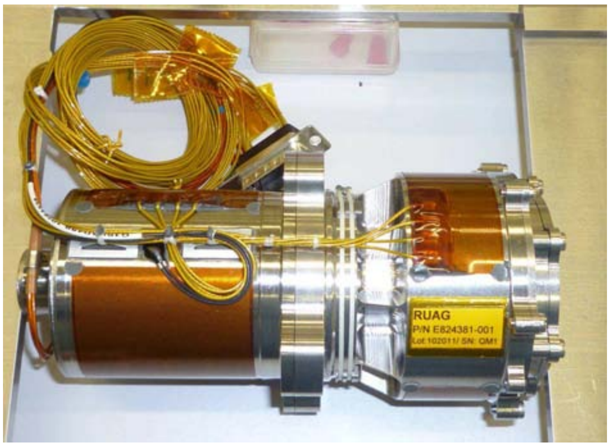

Figure 1. SBGM qualification model 1

After observing the stiffening effect during the random vibration test, a detailed investigation has been performed by analysis identifying three possible root causes for this behaviour of the SBGM mechanism. A stiffness change within the gear as well as a preload loss in the motor duplex bearing could be excluded due to characteristics no fitting with the observed behaviour of the mechanism during the vibration test. The third possible root cause, a stiffness change in the motor single bearing, has been identified as most likely and has also been confirmed by the inspection during disassembly of the mechanism. Fretting marks have been detected on the single bearing outer ring which indicates partial sticking between bearing and motor housing.
As outcome of this root cause analysis, design improvements have been identified to achieve a more robust design. Between single bearing and housing a loose fit has been defined and lubrication (with anti-fretting properties) will be placed in between. In addition, the membrane thickness will be increased to reduce the axial movement of the motor shaft and therefore of the single bearing with respect to the housing. In addition, the frequency of the motor shaft mode is increased into a range where the specified PSD input level is reduced. The investigation process and defined improvements are described hereafter in detail.

'15th European Space Mechanisms & Tribology Symposium – ESMATS 2013'
Noordwijk, The Netherlands, 25–27 September 2013

2 PRODUCT OVERVIEW

2.1. SBGM mechanism

The SBGM actuator consists of a sealed motor with a planetary gearhead attached. A more detailed description of the SBGM and its development approach is shown in [1], [2] and [3]. The SBGM mechanism is depicted in the following figure.

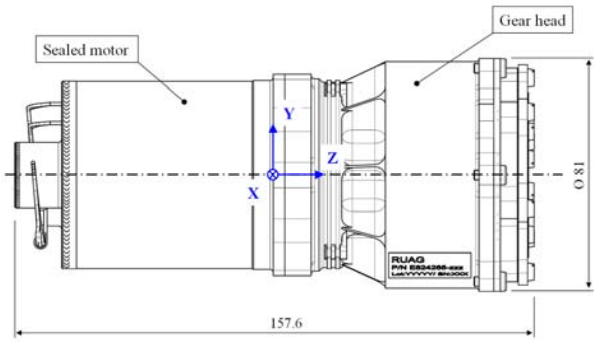

Figure 2. SBGM overview

2.2. Sealed motor

This brush-type DC motor is equipped with two redundant windings and two commutators on the same shaft. The motor is sealed tight in an air filled housing to avoid reliability problems of the brushes behaviour under vacuum (dust, arcing, brush attrition). The motor torque is transmitted to the gear head through the sealing wall by a hysteresis driver coupler. This coupler consists of magnets implemented onto an internal coupler rotor and externally to a hysteresis material stack, which is driven by the magnets through the titanium casing (no mechanical feed through).

The motor axis is supported with a double bearing on one side and a single (floating) bearing on the other side (as shown in Figure 3).

The stiffness of the motor shaft configuration is mainly driven by the design of the rear membrane (as shown in Figure 3).

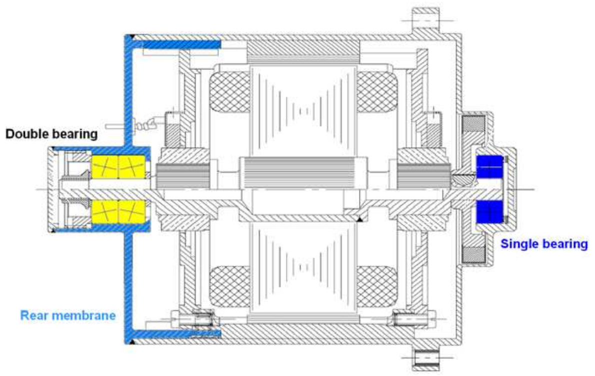

Figure 3. SBGM sealed motor

2.3. Gear head

The gear head is a 4-stage planetary gear with two small stages of the same size and two larger stages with the same diameter but a different width of the gear wheels. The width of the gear wheels is chosen according to their loads and their compatibility with off-the-shelf products (bearings). The gear ratios of the different stages are dimensioned to maximize the gear ratio of the assembly.

3 QUALIFICATION TEST CAMPAIGN (QM1)

Prior to the assembly of the sealed motor and gear head, an acceptance test campaign has been performed at component level (sealed motor and gear head level).

3.1. SBGM qualification test flow

After integrating the motor and the gear head to the SBGM mechanism, the qualification model (QM1) was subjected to a conventional qualification test program as shown in the following figure.

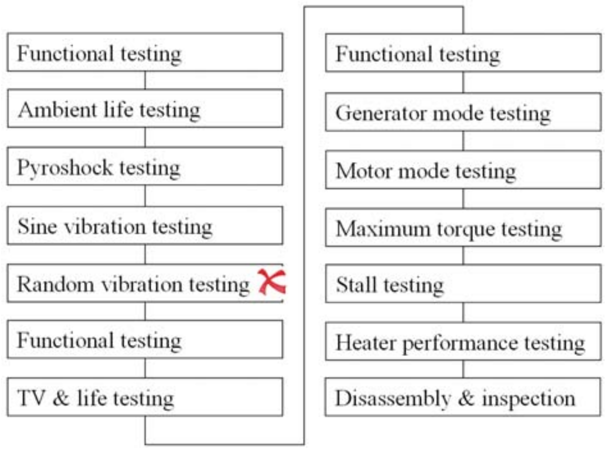

Figure 4. SBGM qualification test flow

The performance tests (like TV tests, generator mode tests, motor mode tests and life testing) in the frame of the SBGM QM1 qualification have been performed successfully throughout the whole test campaign even though the frequency shift during the axial random vibration test was observed.

The remaining content of this paper focuses on the random vibration testing, its (out of specification) results as well as the sub-sequential investigation and the defined way forward.

3.2. Random vibration testing

The success criteria for the random vibration test campaign are given by the ECCS testing standard (ECSS-E-ST-10-03C):

- less than 5 % frequency shift, for modes with an effective mass greater than 10 %
- less than 20 % amplitude shift, for modes with an effective mass greater than 10 %

The vibration tests in radial direction (X- and Y-axes) have been performed within the above mentioned requirements; for the axial direction (Z-axis), the frequency shift measured was above the specification (see Table 1).

SBGM QM1 random vibration testing results			
Accelerometer position	Initial frequency	Final frequency	Frequency shift
X- Axis			
Motor	754 Hz	733 Hz	-3 %
Gear head	733 Hz	708 Hz	-3 %
Y- Axis			
Motor	734 Hz	729 Hz	-1 %
Gear head	754 Hz	733 Hz	-3 %
Z-Axis			
Motor	811 Hz	900 Hz	+11 %
Gear head	811 Hz	900 Hz	+11 %

Table 1. SBGM random vibration test results

4 INVESTIGATION

4.1. Investigation by analysis

4.1.1. Overview

Due to the too high frequency shift of the SBGM during the Z-axis random vibration test, a detailed investigation by analysis has been performed.

The frequency shift measured for the Z-axis configuration concerns the main mode of the motor end around 825 Hz (see Figure 5).

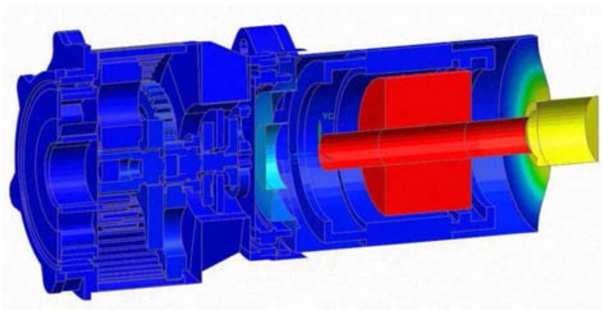

Figure 5. SBGM mode 8 (825 Hz)

The following possible failure cases have been identified as possible causes of the frequency shift during the Z-axis vibration test:

- Gear stiffness change
- Preload loss in motor duplex bearing
- Stiffness change in motor single bearing

4.1.2 Gear stiffness change

The hypothesis that the gear causes the frequency shift has been assessed as very unlikely for the following reasons:

- The concerned mode is driven by the thickness of the rear membrane and the stiffness of the duplex and single motor bearings (as shown in Figure 3).
- A sensitivity analysis with different contact stiffness inside the gear does not lead to any frequency shift in Z-direction.

4.1.3. Preload loss in motor duplex bearing

The hypothesis of a preload loss at motor duplex bearing is assessed to be very unlikely because it would lead to a permanent stiffness reduction (and therefore to a decrease of the final eigenfrequency compared to the initial frequency).

4.1.4. Stiffness change in motor single bearing

For the third failure case, a stiffness change of the motor is assumed due to a change of the stiffness in the motor single bearing configuration.

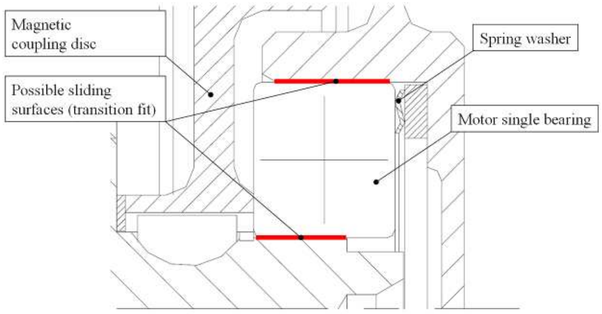

Figure 6. SBGM motor - single bearing configuration

The single bearing configuration is shown in Figure 6 and has the following characterisation:

- Bearing type: deep groove ball bearing.
- Inner & outer rings are transition fitted to shaft and housing (can be loose or press fit).
- Both bearing rings and magnetic coupling disc are free floating without any surface coating or lubrication.
- A slight preload (<1 N) is applied using a spring washer at the outer ring. This preload is based on consideration of acceleration force acting on the outer bearing race mass only.

The following stiffness change scenarios may have occurred:

- Under axial random vibration load, there will be relative motion between the end of the motor shaft and the housing. As the surfaces are uncoated, this could lead to significant fretting wear on the outer ring and/or inner ring (as highlighted in red on Figure 6 and Figure 7) leading to possible adhesion.
- Depending on where the adhesion occurs (partial sticking between bearing and motor housing respectively motor shaft) it could generate an axial load on the single bearing and also on the duplex bearing. This would imply an increase in stiffness of the system.

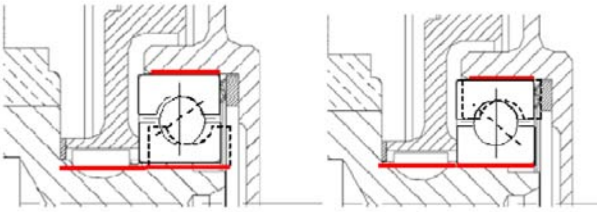

Figure 7. Illustration of sliding of bearing rings

According to FE predictions based on correlation with QM test results, assuming the end of the motor shaft was axially free, approximately 1'300 N would have been encountered at 0dB random on the duplex bearing of the motor shaft. This corresponds to a real motion of about +/- 0.2mm of the motor shaft. This amount is considered to be more than sufficient to cause fretting wear. Assuming the single bearing is no longer free, this will result in an increase of stiffness and frequency as also observed during the test. The following plot shows the predicted frequency increase due to this effect:

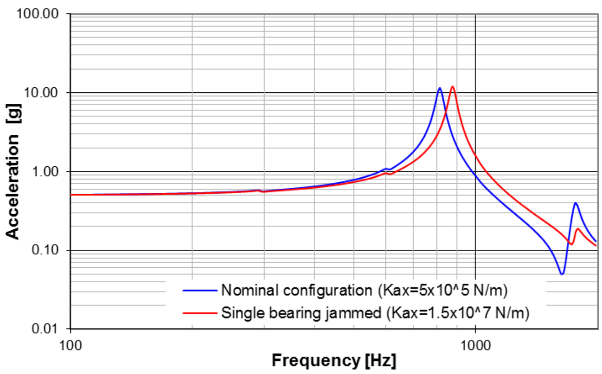

Figure 8. LLS prediction at motor level for Z-axis vibrations - nominal & jammed single bearing

4.1.5. Conclusion of analysis investigation

The hypothesis of stiffness change at motor level due to the design of the floating (single) bearing on the motor shaft is the most probable. The frequency increase of the prediction (Figure 8) corresponds with the results seen during the random vibration test.

To confirm the root cause analysis, it was agreed to perform a detailed inspection during disassembly of the motor (as well as of the gear) at the end of the qualification test campaign.

4.2. Investigation by disassembly and inspection

After finalising the qualification test campaign with the QM1, the SBGM has been dismounted and a detailed inspection, including strip down to parts level, has been performed.

On gear head level nothing unexpected has been found during the disassembly and inspection. This confirms the hypothesis that the frequency shift has not been caused by a change of the gear stiffness.

The inspection of the motor duplex bearing did not show any signs of degradation. Therefore, this root has also been excluded.

During the motor disassembly, special focus has been given to the contact surfaces of the single bearing and the counterpart location of the motor shaft and motor housing.

The inspection of the motor has shown the following observations with respect to the single bearing configuration:

- Traces of friction and probably fretting corrosion visible on the single bearing outer ring (6 blackened zones around the outer ring as shown in Figure 9). On the counterpart (titanium casing bush) some limited axial marks are visible.
- Axial scratches with some minor material deformation in axial direction visible on the rotor shaft at the location of the single (front) bearing. This is most probably a normal result of the assembly process due to the press fit. No signs of movement between the parts (no wear or attrition) could be seen (as shown in Figure 10).

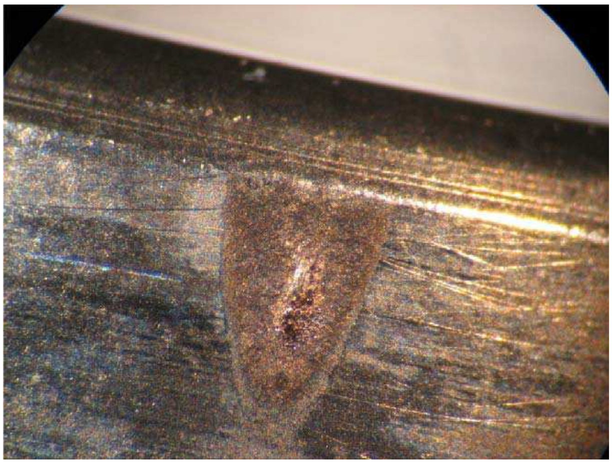

Figure 9. Traces of friction (single bearing outer ring)

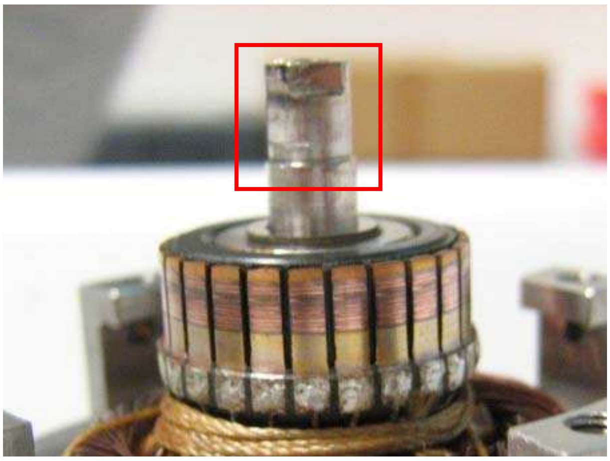

Figure 10. Axial scratches (motor shaft - single bearing location)

4.3. Conclusion of investigation

The outcome of the investigation by analysis has been confirmed by the detailed inspection during disassembly of the SBGM at the end of the qualification campaign. The investigation concludes that the eigenfrequency shift was due to an occasionally sticking of the floating single bearing on the motor housing.

The results and gained knowledge of this investigation have been used to improve the motor design concept. The way forward with the proposed design improvements are shown in the next chapter.

5 WAY FORWARD

5.1. Design improvements

The following improvements will be implemented into the design of the sealed brush motor:

- A press fit has been defined between single bearing inner ring and the motor shaft. Additionally, a chamfer shall be implemented to ensure a proper mounting of the bearing.
- Between single bearing and housing a loose fit will be defined. In addition, lubrication will be placed between outer ring of single bearing and housing (same lubrication as already in the bearing) with anti-fretting properties.
- As risk mitigation, the thickness of the motor rear membrane will be increased (to increase the stiffness and therefore the eigenfrequency of the motor shaft mode). This reduces the amount of relative sliding. Additionally, the frequency of the motor shaft mode in the Z-direction will be increased to a range between 1’000 - 1’500 Hz. This reduces the load due to the fact that the specified PSD input is half compared with the PSD input in the eigenfrequency range of the motor shaft without rear membrane modification.

5.2. Success criteria in axial direction adapted

It has been agreed by all involved parties that the success criteria for the frequency shift in axial direction (Z-axis) is too restrictive and not appropriate for this design due to:

- Soft pre-loaded gear head with disc springs
- Radial gaps between gears
- Only slightly preloaded single bearing in motor

Therefore, the success criterion for the frequency shift in axial direction has been increased to ±8 % (while in radial direction the ±5 % is considered as appropriate).

5.3. Verification

The improved motor design will be verified by re-performing the complete qualification test campaign. The goal of this SBGM qualification test campaign with the QM2 is to confirm the design modification as well as to perform a fully representative campaign according to the ECSS and commercial standards.

6 SUMMARY AND CONCLUSION

After detection of the frequency shift anomaly in axial direction during the random vibration test in the frame of the qualification campaign of the SBGM mechanism, a detailed investigation has been initiated.

The investigation by analysis using a detailed FE-model of the SBGM mechanism has identified a partial sticking of the single bearing as the most probable root cause. Due to this sticking, the eigenfrequency increased by approximately 11 % after the random vibration test in axial (Z-) direction (while the allowed frequency shift is ±5 % according to the ECCS norm).

The visual inspection performed while dismounting the motor confirmed this root cause. Fretting marks were clearly visible on the outer surface of the single bearing.

As outcome of this investigation, design modifications have been elaborated. This modification will be included in an enhanced SBGM mechanism and validated by re-performing the complete qualification test campaign (with the SBGM QM2).

7 REFERENCES

[1] Boesch, C., Langer, U., Zahnd, B., Bonduelle, B., *Development of an actuator for solar-array deployment.* ESMATS 2009, ESA-SP-670.

[2] Schmalbach M., *SBGM QM Final Report,* 851RP0003

[3] Schmalbach M., *SBGM QM Executive Summary,* 851RP0003