MAGNETO-RESITIVE ANGULAR SENSORS FOR SPACE APPLICATIONS: RESULTS OF BREADBOARD AND EQM TESTING AND LESSONS LEARNED

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ABSTRACT

Magnetic microsystems in the form of magneto-resistive (MR) sensors are firmly established in automobiles and industrial applications. They are used to measure travel, angle, electrical current, or magnetic fields. MR technology opens up new sensor possibilities in space applications and can be an enabling technology for optimal performance, high robustness and long lifetime at reasonable costs. In some science missions, the technology is already applied, for instance in case of the angular sensors used for JPL/NASA's Mars rover Curiosity [1]. However, the designs are proprietary and case specific.

Since 2013 HTS GmbH and Sensitec GmbH have teamed up to develop and qualify a standardized yet flexible to use MR angular sensor for space mechanisms. Starting with a first assessment study and market survey performed under ESA contract [2], a very strong industry interest in novel, contactless position measurement means was found. Currently a detailed and comprehensive development program is being performed by HTS and Sensitec. The objective of this program is to advance the sensor design up to Engineering Qualification Model (EQM) level and to perform qualification testing for a representative space environment.

The paper briefly describes the key benefits of MR angular sensors with reference to currently operational industrial and space applications. The key applications and specification are presented and the preliminary baseline mechanical and electrical design will be discussed. An outlook on the upcoming development and test stages as well as the qualification program will be provided.

INTRODUCTION

Magnetic microsystems in the form of magneto-resistive (MR) sensors are established in various industries: automobiles, mobile telephones, medical devices, wind turbines, machine tools or industrial robots, be it for the measurement of travel, angle or electrical current, or as an electronic compass. Originally developed for data storage applications, the various MR effects open up new measurement possibilities for sensors, not only in terrestrial applications, but also in space applications.

MR sensors are robust, reliable, precise and miniaturized. This combination of features is leading to continuous growth in the application field of MR sensors. The extremely low power consumption of MR sensors make them ideal for wireless, autonomous sensor applications. They present completely new possibilities to the developers of many different types of mechanisms or instruments to measure angle, path, electrical currents, or magnetic fields.

The interest in MR technology from the space community is growing, in particular since the successful application of 40 MR angle sensors to control the motion of electric motors on the Mars Rover "Curiosity" as part of the Mars Science Laboratory Mission [1]. This was not the first application on Mars – MR sensors were already used on the Mars Exploration Rovers Mission to control numerous motors on "Spirit" and "Opportunity".

All these sensors were designed and manufactured by Sensitec GmbH, located in Lahnau, near Wetzlar, Germany. MR sensors from Sensitec will also be used for the precise positioning of a miniaturized low-mass optical shutter for the MERTIS thermal infra-red imaging spectrometer within the BepiColombo mission to Mercury. Furthermore, MR-based current sensors are likely to be part of the power electronics driving the Thrust Vector Actuators of the Ariane 6 launcher.

Until now the growth in MR applications in space has been opportunistic, with the result that there has been considerable duplication of effort when developing sensor solutions specifically for use in space. In order to focus the effort and to fully exploit the benefits of MR technology for European space mechanisms and applications, HTS GmbH and Sensitec GmbH initiated a close collaboration, leading to dedicated activities for the design and qualification of MR-based angular sensors for space applications. HTS GmbH is located in Coswig, Germany specializing in the development and manufacturing of mechanisms for spacecrafts.

SPECIFICATION OF THE MRS APPLICATIONS

In general, MR-based sensors possess the unique advantage that in order to comply with low or medium

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performance demands (i.e., up to 11 bit resolution), basically no front end signal conditioning is required to provide the user with a reasonable angular signal due to the intrinsic sine-cosine output signal. In order to achieve discrete (hence TTL compatible) sensor output signal, only a reduced signal processing is required. This is desired by most potential users and makes this concept an ideal candidate for low to medium performance 360° incremental encoders with a reference pulse. Such sensor can be used to replace potentiometers in mechanisms in order to improve reliability, performance and to keep the costs at low level, or to enable closed-loop motor control for improved mechanism performance and reduced microvibrations. Such medium performance encoder could be used for instance for:

- Antenna pointing mechanisms
- Shutter mechanisms
- Calibration mechanisms
- Reaction wheels (e.g., as wheel speed sensors)
- Robotic exploration (e.g., wheel position sensors, as already used in case of the Curiosity Rover [1])

As a baseline for the design of the Magneto-Resistive Angular Sensor for Space Applications (MRS), a dedicated pilot application was selected, and the technical requirements were derived. The baseline specification is given in Tab. 1.

It is worthwhile to highlight that the AMR and GMR sensors developed and produced by Sensitec allow for various sensor concepts; hence it is also possible to design and qualify mission-specific or user-specific encoders, allowing for true power-on absolute angular measurements, or high resolution and high accuracy angular measurement.

Requirement	**Value**
Angular Range	360° (no deadband)
Rotational speed	> 100 RPM
Resolution	> 10 bit (~0.3°)
Repeatability	< 0.5° (goal: 0.1°, TBC)
Measurement type	Incremental with reference pulse
Output signal	Digital ABZ (TTL)
Power consumption	< 150 mW (TBC)
Lifetime	on ground: > 15 years, in orbit: > 15 years
Temperature, operational	-50°C ... +100°C
Temperature, non-operational	-60°C ... +110°C
Radiation hardness	> 250 krad
Mass	< 150 g

Table 1 MRS Key Requirements Specification

BREADBOARD DESIGN

The design for breadboard testing consisted of two mechanical housings. The lower stage, as shown in Fig. 1 accommodated two sensor assemblies (nominal and redundant). Each of these assemblies comprised a pre-amplification for the MR chips. An AMR chip was used to provide a sine/cosine signal from the passing incremental track of the pole ring. A GMR chip was engaged to give a once per revolution reference pulse. The rotor has a second (datum) track magnetized for that.

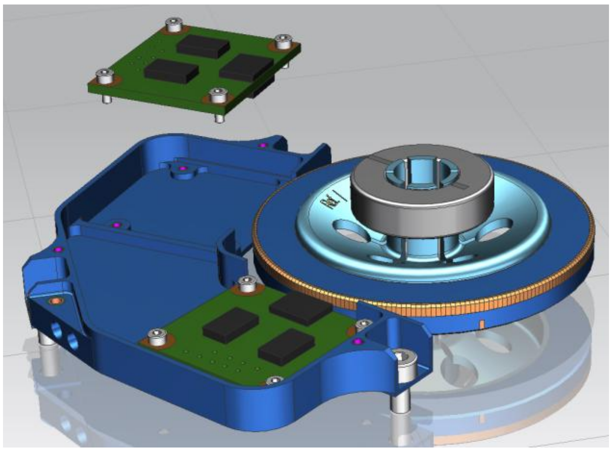

Figure 1Sensor and rotor assembly

The second stage housing (see Fig. 2) contained the nominal and redundant signal conditioning PCB for the ABZ signal output option.

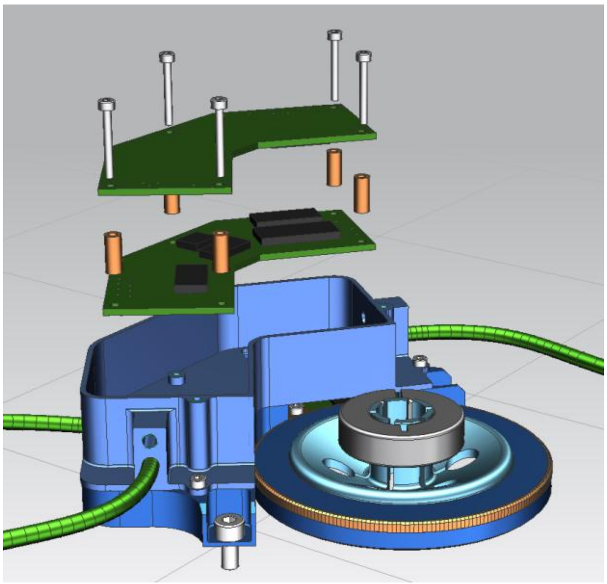

Figure 2

The rotor design which basically enables the mounting of the pole ring has a clamped connection to a corresponding shaft. This allows for investigation of different axial positions during testing.

TEST RESULTS

Before finalizing the EQM design a comprehensive test campaign on component, electrical subsystem and breadboard level was carried out to proof the concept, detect possible design issues and develop the test equipment in parallel. Some of the major results will be presented in the following.

1.1. Radiation test

A radiation test was performed with 21 samples of three different MR sensor types (AL798, AL803, GF708). The sensor chips resistance was measured before and after irradiation. Receiving total dose of the samples was staggered in 50krad, 100krad, 300krad, 1000krad and some samples were exposed to 14MeV neutron flux.

The two AMR sensor chips showed negligible differences in the before-after measurements (Fig. 3) for all irradiation doses. The GMR sensor also proofed radiation hardness.

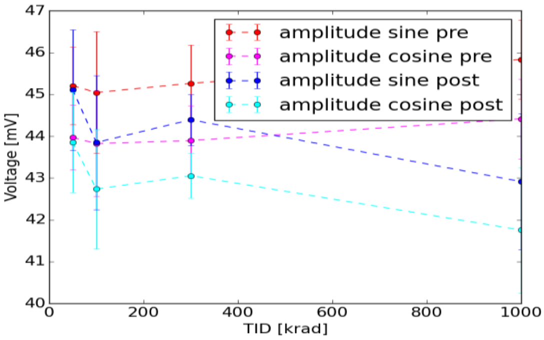

Figure 3 pre and post test signal amplitudes

1.2. Magnetization test

The pole ring magnetization was tested and evaluated as angle error over a full rotation (Fig. 4). The main factors of influence are the mechanical eccentricity of the rotor and the start/end position of the magnetization which is causing a variation of the magnetic pole width.

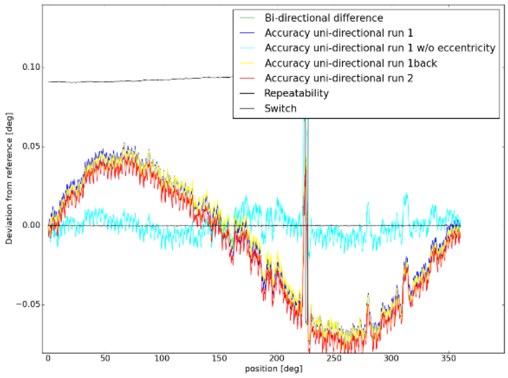

Figure 4 excentricity error test at component level

Inspection of the magnetic poles and measurement of the field strength was done at the pole rings (Fig. 5)

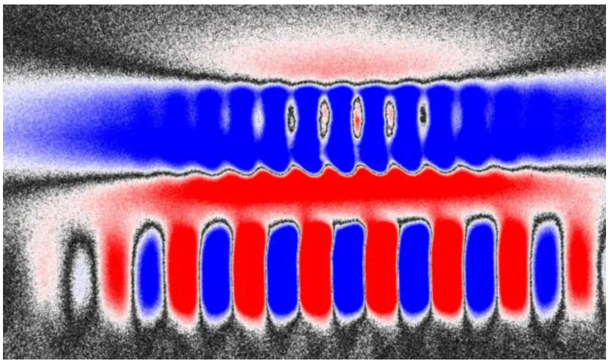

Figure 5 manetic field strengh of incremental track inspected with magnetic camera

1.3. Electrical subsystem tests

The electrical subsystem consisting of pole ring, sensor board and signal board was subjected to tests of accuracy, repeatability, hysteresis and signal amplitude/offset etc. The main findings are:

- Repeatability of sensor is +/-0.002°
- Uncertainty of sensor without eccentricity error is 0.1°
- Electrical hysteresis of signal BB varies with signal amplitude from 0.03°(1Vpp) to 0.22° (0.15Vpp)
- Signal amplitude changes with temperature from 0.42Vpp (at -40°C) over 0.3Vpp (at 25°C) to 0.19Vpp (at 100°C)
- Pulse stability of the signal was successfully tested up to 5kHz

1.4. Breadboard test

Breadboard (BB) test intension was to characterize the system as a whole, coupling mechanical and electrical components. The test campaign included several parameters, e.g. speed, air gap, axial potion of rotor, temperature.

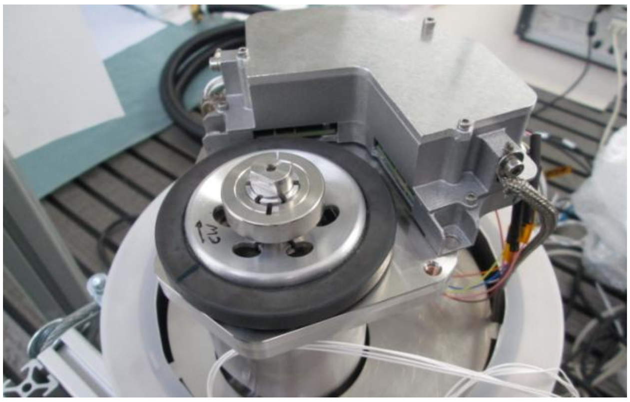

Figure 6 BB hardware mounted in test stand

For tests at BB level and later qualification a versatile test stand was developed enabling functional testing and testing under thermal and vacuum environment (see Fig. 6 and 7).

A stepper motor with gear stage and a mechanical vacuum tight feed through were engaged to motorize a typical arrangement of shaft with preloaded bearings in face to face configuration. The MRS breadboard was located on one end of the shaft close to heaters and a cooling pipe coil. Opposite a vacuum compatible optical encoder was attached to the same shaft in moderate thermal environment, serving as reference measurement system.

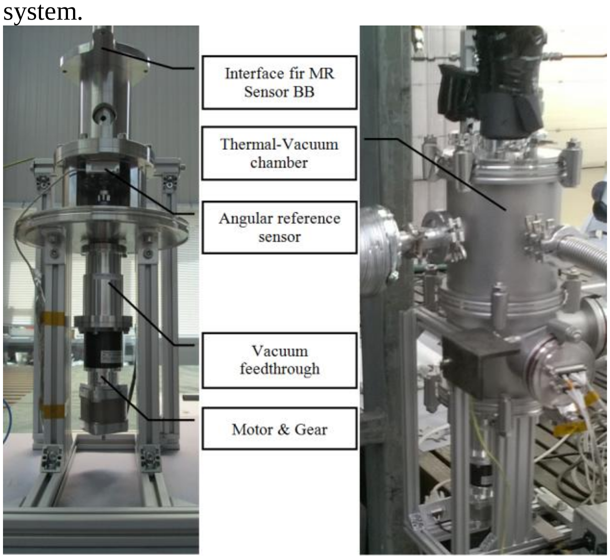

Figure 7 test stand (performance &TVC)

First tests with variation of speed and rotation direction were conducted. At low speed the angular RMS error of the nominal and redundant MR Sensors was about 0.1°. At higher rotation speed RMS error increased, however the absolute deviation of the angle at stop position was still low. Since final position accuracy was not impaired the conclusion was drawn that the measurement hard/software caused this RMS error increase. The time gap between retrieving the MRS angle and the Reference angle becomes considerable at higher speed. So the set up need improvement for EQM testing campaign.

A considerable high influence on the angular measurement uncertainty has the excentricity of the rotor assembly. In Fig. 8 a typical error plot is shown. First observation is a 360° repeating wave in the error plot caused mainly by excentricity is visible. Second high spikes which also repeat every 360° for the nominal and redundant channel as well are noticed. These turned out to be caused by magnetic crosstalk of the passing datum pulse to the incremental track.

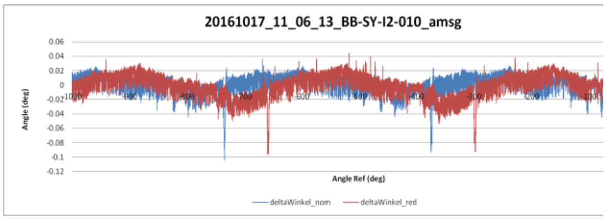

Figure 8 typlical absolute error recorded during BB testing

The reference pulse track on the pole ring is serving as an indication of the absolute position. Repeatability of reference pulse was measured with the analog signal by detecting the first falling flanks. Repeatability was less than 0.005° over multiple rotor turns.

A performance driver of the measurement system is the air gap between pole ring and chip housing, because it directly influences the magnetic field strength seen by the chip. The MR chip housing is placed right at the front edge of the board and variation of air gap was done by direct adjusting with a feeler gauge. As expected the error increased with larger gap size (Fig. 9). Correspondingly a lowering in analogue signal amplitude was detected. Optimal would be an operation at about 200 µm distance.

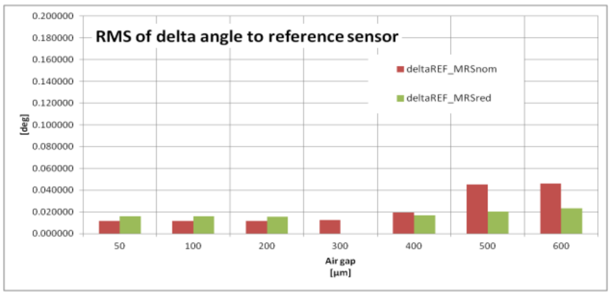

Figure 9 RMS error of the analoge signal at different air gap sizes

For the ABZ signal output the error is approximately at the same level up to the point where the weaker signal amplitude from sensor causes a failure in the pulse generation of the signal conditioning electronics. This was the case at about 500-600 µm air gap for one of the two tested channels (see Fig. 10).

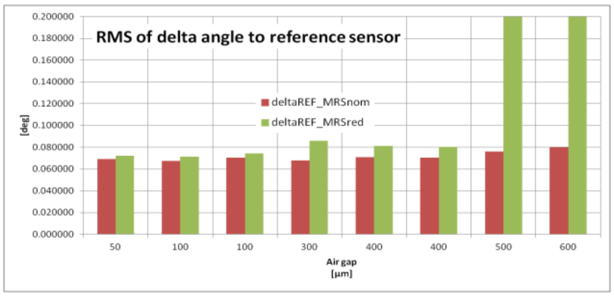

Figure 10 RMS error of the ABZ signal at different air gap sizes

Tests at hot/cold environment in the range of -40°C up to +80°C resulted not in considerable different behavior as for room temperature.

TEST RESULTS SUMMARY

Parameter	ABZ Signal (BB Test)	Analogue Signal (BB Test)
Angular Measurement range	> 360° without dead zone	> 360° without dead zone
Resolution	10.8 bit	~16 bit equivalent with 12 bit ADC
Linearity error	< 0.14°	<0.1°
Repeatability	±0.05°	<0.005°
Temp. Range	-40 … 80°C tested	-40 … 80°C tested
Signal Type	TTL (0-5V)	Analogue 1 Vpp max.
Radiation Level	> 250 krad	300 krad

Table 2 BB performance summary

LESSONS LEARNED FROM BB TESTING

The BB testing campaign delivered valuable inputs into the design of the EQM. Problematic areas are for instance the error caused by eccentricity and magnetisation. Mechanical runout will not be possible to exclude completely. However the grinding process of the outer diameter of the pole ring before magnetisation showed reasonable improvements. A crosstalk of the reference pulse (located at magnetization start/stop position) will be prevented for the EQM by putting the magnetic tracks more distant from each other. In addition the magnetization of the start stop position will be improved to reduce pole size variation.

In terms of the design the housing concept of the BB was found bulky and adverse for harness routing. A revision of the design resulted in a modular approach for the EQM as shown in the following.

MRS EQM SENSOR DESIGN

Based on the elaborated specification, a MRS design has been developed.

In its baseline configuration, the encoder will be in an off axis arrangement (Fig. 11). The rotor comprising the pole ring, an adapter and a clamp ring is mounted to the shaft or other rotating part of a mechanism.

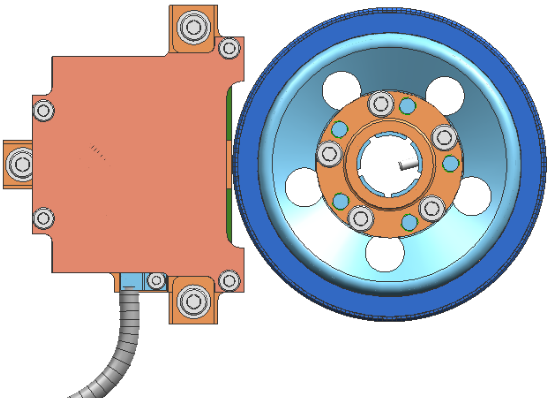

Figure 11 configuration with analog output 1Vpp

The sensor assembly and the signal processing are accommodated in separate housings. These are fixed to the static part of the mechanism. The spatial separation of sensor assembly and the signal processing assembly offers more flexibility. It need less space in the vicinity of the sensing location and enables modular and redundant configurations (Fig. 12).

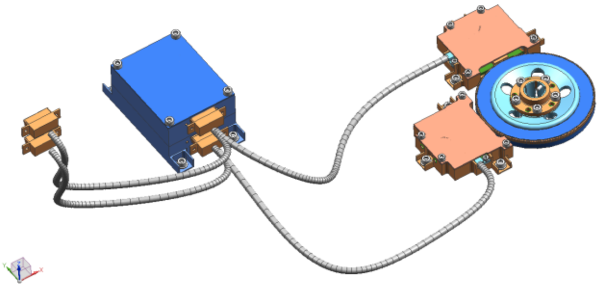

Figure 12 redundant configuration with signal processing (output 0/5V ABZ)

The pole ring which represents the magnetic scale has a diameter of 72 mm. One track is magnetized with 230 poles. A second track comprises a single pole generating a reference signal for a full rotation. The rotor assembly design of the EQM has a lightweighted clamping design and also a option for direct mounting with screws (Fig. 13)

An AMS chip uses two magneto-resistive areas generating a sinus and cosines voltage amplitude when passing a pole. The signal board uses this output to generate 8 flanks per pole, which result in a resolution of 10.8 bit.

Variations in pole ring size are possible. However since the pole width shall be 1 mm the reduction in diameter is also resulting in lower resolution. The used of the shelf pole ring is rather massive, but an optimization of radial thickness with a grinding process is possible to fit between standard sizes.

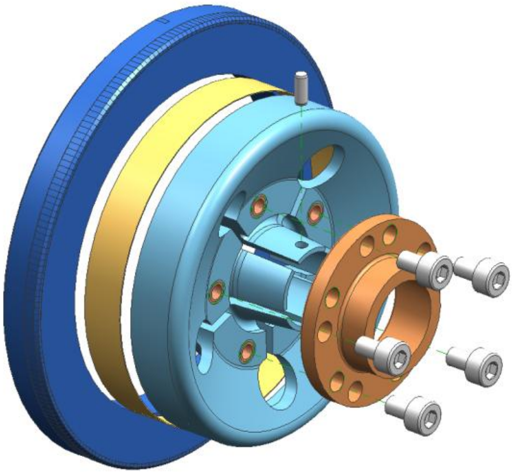

Figure 13 rotor assembly

The sensors will be housed in a dedicated LTCC (low temperature cofired ceramacs) package, conforming to ECSS outgassing and quality standards. The sine cosine signals can be delivered directly as 1 Volt peak to peak. Depending on utilized ADC for signal processing resolutions significantly higher than 15bit are possible. However, often a discrete signal (TTL signal) is required by the controller. In order to provide this interface, a dedicated signal board is included in the measuring system, which transforms the sine-cosine signals into a TTL-compatible pulse signal (ABZ, 0 - 5V).

This is achieved by a set of comparators and operation amplifiers, which allow deducing a pulsed signal with four pulses per pole from the pre-amplified sine-cosine signals. The resulting resolution is of about 0.3°. The A and B pulses are phase shifted, allowing determination of the rotation direction.

CONCLUSION AND NEXT STEPS

The objective of this activity is to develop and qualify an MR-based contactless angular position sensor in order to achieve swift and efficient entry into the market.

The technical requirement specification has already been consolidated and finalized based on a relevant reference application. Currently, the MRS EQM design is manufactured and corresponding test planning ongoing.

Engineering Qualification Models of the MRS shall have TRL 6. All used electrical components are already qualified. The qualification tests on EQM level include functional performance tests at ambient and thermal vacuum, vibration and shock tests, electro-magnetic compatibility and electro-static discharge tests (EMC, ESD) as well as outgassing tests and radiation tests.

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