REED: THE MANUAL

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ABSTRACT

Microswitches are commonly used to indicate a successful deployment, by the positional monitoring of mechanisms or deployable structures. Microswitches are so-called Single-Pole, Double Throw tactile switches, whose operation is perceptible by contact. Although microswitches are extremely reliable at component level, they come with challenges when integrated at mechanism level. As an alternative solution, Airbus Netherlands is working on a sensing method using Singe-Pole, Single Throw Reed Switches which are magnetically activated. This paper will describe the approach taken for the development of Airbus' Reed Switch Assembly and will provide the acquired insights and lessons learnt during this development.

1 INTRODUCTION

1.1 Microswitches versus reed switches

Typical microswitches used in space mechanisms are Single-Pole, Double Throw (SPDT) tactile switches (see left switch of figure 1). At component level these microswitches are considered extremely reliable, however integration in deployment mechanisms comes with several challenges:

- A force is needed to activate the microswitch. The friction or retarding force induced by the switch needs to be limited.
- The microswitch has a small operational range; the so-called overtravel – the distance the microswitch may be pushed in after activation – is around 1/10th of a millimetre. Additionally, the differential travel (or hysteresis) is larger than the overtravel, making it difficult to properly adjust the microswitch.

Figure 1. Left: Typical microswitch, right: typical reed switch. Size to scale

Care has to be taken when installing and aligning these switches. The limited operational range and hysteresis requires that the microswitch is properly aligned at mechanism level. Additionally, the design should be made roboust for misalignment, coupliance, thermo-elastic effects and others to avoid any impact on the performance of the switch. The short overtravel range could be increased by adding a lever arm onto the microswitch, however this also increases the hysteresis and built volume, which are highly undesired in high precision mechanisms.

An alternative approach is to rely a sensing method using commercial of the shelf (COTS) Reed Switches, a Single-Pole, Single-Throw (SPST) magnetically activated switch. A reed switch – as shown on the right in figure 1 - consists out of two ferromagnetic metal plates inside a hermetically sealed glass tube. Introducing a magnetic field – with sufficient magnetic flux in axial direction of the reed switch – the blades of the reed are attracted to each other, make contact and the electrical circuit is closed.

The advantages of the reed switch is its contactless operation; a significant advantage for a deployment mechanism. In addition, the limited volume of the reed switch and the contactless operation allows for more and different design configurations with improved capabilities. A third significant advantage of the reed switch is the large operational range. This range can be changed by a different configuration of the reed and magnet. It has been determined that a range of several millimetres is preferable for solar arrays as it is results in a more robust sensing design.

During the beginning of the development efforts of the reed switch, the following possible challanges of using reed switches – as compared to microswitches – have been identified:

- Detailed information on the functional performance of reed switches is scarcely available and that what is available is vague, not concrete and therefore unpractical; hence a more detailed understanding of the reed switch performance is needed and a more detailed physical model is needed to predict its performance.
- Reed switches are mostly available in its raw form, hence it has to be adopted in some way to practically implement it in a mechanism design
- No space qualified reed switch is available within

Europe. US originated space qualified reed switches are available, but considered not reliable [1].
- Commercially available reed switches from European manufacturers are available, but it is not certain whether they can withstand the harsh space environments. Hence, early phase environmental testing is required to determine the performance of the reed.

All these aspects have been dealt with during the developments of the reed switch for space application and will be addressed in the following sections.

1.2 Reed Switch Assembly Design Description

Based on learnings from several design iterations, early phase testing and manufacturing trials, a baseline design of the Reed Switch Assembly (RSA) has been obtained. The current design is shown in shown in figure 2. The Reed Switch Assembly consists of the following components:
- Reed Switch: KSK-1A87 Series Reed Switch produced by Standex Electronics [4]. The leads of the Reed Switch are trimmed to length and bend pending the required configuration.
- Carrier plate: A PEEK base plate element of the RSA to mount all electrical components
- Space qualified crimp splices
- Flying leads

A detailed breakdown of the RSA is shown in figure 3.

Figure 2. Photographs of two Reed Switch Assembly Engineering models

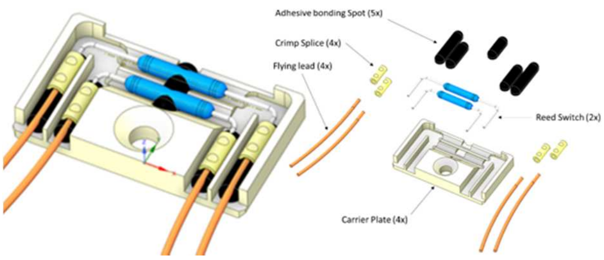

Figure 3. Components Breakdown of a redundant Reed Switch Assembly

1.3 Reed Switch functionality

A reed switch consists out of two ferromagnetic metal blades inside a hermetically sealed glass tube separated with a typical distance of 25 microns, see figure 4. The reed switch is activated upon the presence of magnetic field, either from a magnet or by a coil.

When the magnetic flux at the reed has a specific magnitude and orientation with respect to the orientation of the reed blades, it magnetizes both ferromagnetic blades such that the closing force between the north- and south-pole is sufficient to overcome the stiffness of the blades. This results in an electrically closed circuit between the two leads of the reed switch. The external field strength required for this activation is called the Pull-In value.

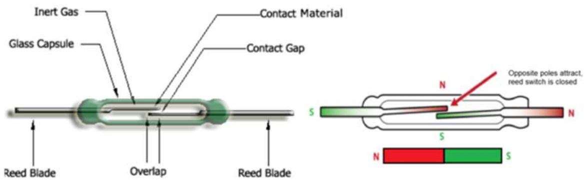

Figure 4. Reed Switch components (left) and functioning when magnetized (right)

For a closed reed switch, the blades have an influence on the magnetic fields, which causes the reed switch blades to 'stick' to each other once closed. When the external field is reduced enough, the blades will eventually break contact. The value of the external field at which the reed switch deactivates is called the Drop-Out value and is always lower than the Pull-in value. The difference between Pull-In and Drop-out can be considered as the hysteresis within the system.

Within the reed community, the Pull-in and Drop-out (PIDO) values of a reed switch are defined in Ampere-Turns. This assumes that the reed switch is activated by a coil with a certain amount of coil windings (turns) with a certain current running through the coil. The magnetic field strength of a coil is described by Eq. 1

$$B = \frac{\mu_0 \cdot N \cdot I}{L} \tag{1}$$

Where B the magnetic flux is defined in Tesla, μ_0 is the vacuum magnetic permeability, N is the number of coil turns, L is the coil length and I is the current passed through the coil. However, when using the units of Ampere-Turns, one should know the details test coils of the manufacturer. Therefore, using Ampere-turns does not allows to make a direct comparison between reed switches of different manufacturers. A more standardized approach is to define the PIDO values as function of magnetic flux in units of Tesla.

The rationale to express the PIDO values in units of Tesla, is that at mechanism level the Reed Switch shall be activated by a magnet. For a magnet, the magnetic field strength and orientation is dependent on the position, this in comparison to the uniform magnetic field that is generated by a coil. A typical example of a magnetic field around a cylindrical magnet is shown in figure 5. The left graphs shows a decreasing magnetic flux when measured further away from the magnet, as well as a different orientation of the field lines. As the reed switch is mainly sensitive for the magnetic flux in the direction of the blades, the user is interested in the effective magnetic flux in only one particular direction, such as shown on the right of figure 5. This graph shows that for this particular configuration there are specific lobes at which the reed is activated. Illustrative PIDO zones of the reed are available in literature, such as shown in figure 6 [3].

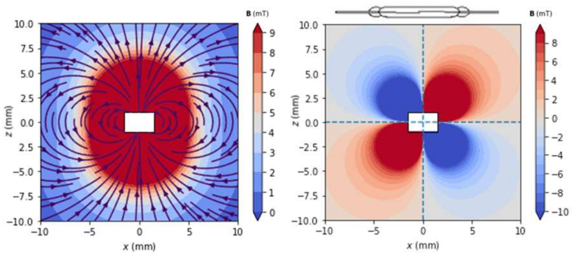

Figure 5. Total Magnetic flux and field lines (left) and magnetic flux in x-direction (right)

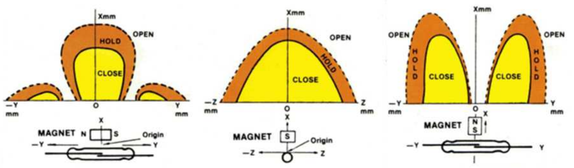

Figure 6. Typical shapes of the pull-in and drop-out zones of a reed switch [3]. Left and middle: Magnet parallel to reed. Right: magnet perpendicular to reed.

Although the graphs in figure 6 give an indication of the PIDO zones, no exact dimensions are given. Unfortunately no further detailed information on the exact shape of these zones has been found in literature, neither a proper way to determine these zones.

2 DEVELOPMENT APPROACH

Given the wide variety of mechanisms used and being developed at Airbus Netherlands, it has been decided to aim for a full in-house development of the RSA based on COTS reed switches. The rationale to rely COTS reed switches is to have more flexibility to use the reed switch in any configuration in its assembled form, while on the other hand limiting procurement costs. If a design change of the RSA is required, this could be more easily implemented if all development and qualification aspects are performed by Airbus Netherlands.

The key development aspects are to:

- Acquire all needed knowledge to develop an analytical model to predict the functional performance – i.e. the PIDO zone – of a RSA when activated by a magnet.
- Develop manufacturing tooling for the modifications on the reed switch such that it can be assembled in the RSA.
- Develop test tooling for the verification of the functional performance and the verification of the reed switch's health.
- Environmental testing combined with electrical health checks and functional characterization tests.

More details and the rationales on these aspects are provided in the subsections hereafter. Details on the performed activities are provided in the sections 3 and 4.

2.1 Analyses and verification approach

For a proper implementation of the RSA and the magnet into a mechanism, the exact position and orientation need to be known to determine when the reed switch is activated and de-activated. In particular for early-phase developments of mechanism, it is more convenient to determine the required configuration of the reed and magnet by an analyses model, prior to verification by testing.

For this reason an analytical model is developed, verified and correlated to predict the PIDO zones of any reed-magnet combination. The goals of this development are:

- Create an analytical model to predict the PIDO zones for any reed-magnet combination
- Determine the validity of the analytical model by performing magnetic measurements and PIDO measurements
- Perform a correlation study between the analytical model and test measurement, identify any discrepancies and update the model were needed.

Details of this development are presented in section 3.

2.2 Procurement and manufacturing approach

A COTS reed switch is chosen for the following reasons:

- COTS items have a reduced cost, compared to a procurement of reed by specification. Especially if the reeds are procurement with the requirement to survive the stringent environmental, this will result in additional efforts which are preferably done at RSA level instead of on reed level.
- It is not foreseen that there is a hardware difference between COTS items versus items ordered under a specification, hence its performance will be identical.

COTS reed switches might have a lower procurement cost, but comes with certain challenges and risks. The supplier commonly performs a health screening, however this is performed prior to modifications the reed, Therefore no guarantees are made on the reed performance after any modification. To deal with this, the following procurement and verification approach is foreseen:

- A batch of a couple of thousand reeds are procured, all from a single production lot.
- All these reed switches will be subjected to thermal vacuum cycling tests (TVAC), prior to putting the reed switches on stock.
- Roughly 50 of these cycled reed switches will be used for the production of the RSA test articles and are subjected to qualification testing. This will qualify the entire procured batch, with in particular the developed production process and the extended environmental conditions.
- The remainder of the reeds on stock will only be used when needed. Once assembled in the RSA, acceptance health tests will be performed to validate the integrity of the reed switch after the manufacturing steps. Hence a 100% screening is performed. As the reed switches have been subjected to TVAC at unit level, no further environmental acceptance testing shall be performed at RSA level.

2.3 Environmental and health testing approach

Solar array mechanisms - and therefore also the RSA - will be subjected to extreme environmental conditions. Since these conditions are far beyond the specified operation ranges of the reed switch additional environmental testing is foreseen [4].

In order to perform the functional verification during environmental testing and to perform electrical health acceptance tests, dedicated hardware and test algorithms have been developed.

3 ANALYSES MODEL AND VERIFICATION

The purpose of the analytical model is to have a simplified representation of the reed switch and magnet capable of determining when the reed is activated and de-activated. The first modelling approach the following assumptions are made:

- The magnetic flux shall be models using the magnetic dipole model. This allows to determine the magnetic flux in any direction for any position in space. It is assumed that this model is accurate enough for these analyses.
- The reed switch shall be modelled as a point sensor, to simplify the analyses efforts. The reed switch is modelled as a sensor with different states, either de-activated, activated or within the hold-on zone (or hysteresis zone); each state of the reed switch will be defined by its threshold magnetic fluxes.

3.1 Magnetic dipole model

The magnetic flux of the magnet is derived from a magnetic dipole model based on the Biot-Savart law. The magnetic fluxes can be described by equation 2.

$$\boldsymbol{B}(\boldsymbol{r}) = \frac{\mu_0}{4\pi} \cdot \left[\frac{3r(\boldsymbol{mr})}{r^5} - \frac{m}{r^3} \right] \tag{2}$$

In which $\boldsymbol{B}(\boldsymbol{r})$ is the total magnetic flux at this point and $\boldsymbol{m}$ equals the magnetic moment of the magnet. Using $r = (x^2 + y^2 + z^2)$ and $\boldsymbol{mr} = m_z z$ the separate orthogonal Cartesian components of B_x, B_y and B_z can be calculated. This results in the following equations:

$$\begin{aligned} B_x(x,y,z) &= \frac{3m \cdot \mu_0}{4\pi} \cdot \left[\frac{xz}{(x^2+y^2+z^2)^{\frac{5}{2}}} \right] \\ B_y(x,y,z) &= \frac{3m \cdot \mu_0}{4\pi} \cdot \left[\frac{yz}{(x^2+y^2+z^2)^{\frac{5}{2}}} \right] \\ B_z(x,y,z) &= \frac{3m \cdot \mu_0}{4\pi} \cdot \left[\frac{z^2 - \frac{1}{3}(x^2+y^2+z^2)^2}{(x^2+y^2+z^2)^{\frac{5}{2}}} \right] \end{aligned} \tag{3}$$

Where the magnetic moment is calculated by:

$$m = \frac{1}{\mu_0} \boldsymbol{B_r} V \tag{4}$$

Where: $\boldsymbol{B_r}$ is the residual flux density, expressed in Tesla, V is the of the magnet in m^3, μ_0 is the permeability of vacuum $4\pi \cdot 10^{-7}$ in [H/m]

The use of the dipole model relies on two important assumptions.

- The PIDO transition zones of the reed switch are far away from the magnet. A dipole model is only valid for far-field analyses, but not in the close vicinity of the magnet. Studies have shown that the magnetic modeling at these PIDO transition zones are accurate. Only at close distances from the dipole center – roughly up to 2 times the major magnet dimension – there are significant differences between a dipole model and a geometric magnetic model, see figure 7. Beyond these dimensions, the differences between the models are negligible or acceptable for this particular application.
- This model does not assume any non-linear magnetic effects such as saturation. As these effects only occur at high magnetic strengths which are far away from the PIDO transitions, these can be neglected.

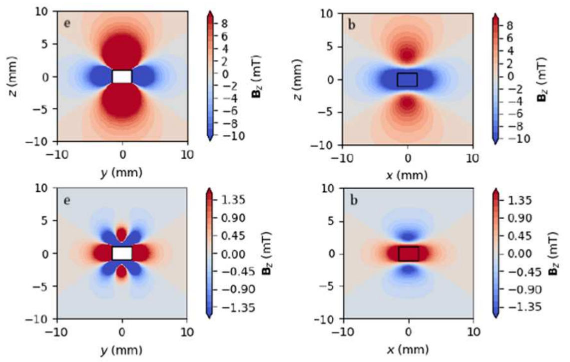

Figure 7. Calculated fluxes by dipole model (top) and delta flux between dipole and geometric model (right)

3.2 Reed Switch Pull-In Drop-out values

Although the reed switch characteristics are often provided by the manufacturer, these do not always provide all the required information of the reed performance:

- Often only the Pull-in value is provided, not the drop-out value
- The mentioned pull-in value has a high uncertainty range, for sensitive reed switches this can be between 25% to 50%
- The provided pull-in value is for a reed switch without any alteration on it. In case modification of the reed, such as for trimmed and bend leads, the PIDO value increases, hence making the switch less sensitive.

Given the above reasons, further analyses shall not rely on the provided values from the reed manufacturer datasheet. Dedicated PIDO measurements are performed using a Helmholtz coil to create a magnetic field, see figure 13 and section 4.2. This way, the exact PIDO values of the reed switch is determined, which can be used for modelling and correlation purposes of the analytical model.

3.3 PIDO zones modelling vs. measurements

Based on the analysed magnetic fluxes from the magnet and the measured PIDO values from the reed, PIDO zones are derived as shown in figure 8. Comparing these zones with figure 6 from literature shows similar shapes, however there is a significant difference when comparing them in detail.

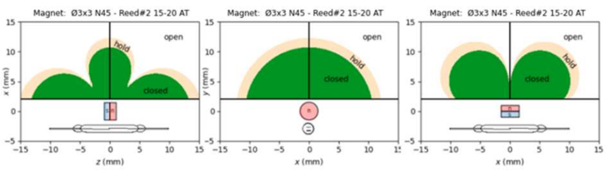

Figure 8. Resulting PIDO zones analysed with the initial model. Based on a magnetic moment of 11.5mA·m² and a reed PIDO of 0.63mT and 0.93mT

With the use of a non-magnetic 3-axis linear translation stage, the PIDO values of a reed- combination has been determined. Results of these measurements compared with the results from the initial analytical model is shown in figure 9. This comparison clearly shows that the shapes are similar, however the measured zones are squished to approximately 60% of the analysed zones. It should be noted that although the zones are reduced by nearly half, the magnetic fluxes differs with a factor of 2 to 5.

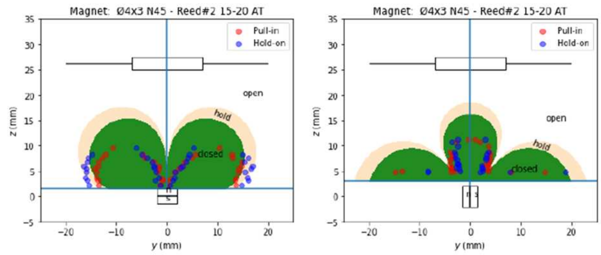

Figure 9. Comparison between measured PIDO zones and analysed zones from the initial model.

Detailed investigations have ruled out several possibilities which might explain the difference in the PIDO zones:

- Validity of the magnetic dipole model: As mentioned the magnetic dipole model is only valid for far-field results and not close by. Magnetic measurements have been performed which indicate the validity of the dipole model in the region of interest.
- Hysteresis or non-linear magnetization: In case of high magnetic fluxes, a non-linear magnetization might occur. Detailed analyses show that the non-linear zones are far inside the PIDO zones and are not a probable cause.
- Influence of the reed switch on the magnetic field: due to the presence of the reed switch, the magnetic field might be effected. Magnetic field measurements have been performed with and without the reed switch present, however no significant changes are observed.

The most likely false assumption made in the modelling approach - as stated in section 3 - is that the reed switch sensor can be modelling as a point sensor. Figure 10 shows the magnetic field lines, which are non-uniform over the length of the reed, both in strength and direction of the flux.

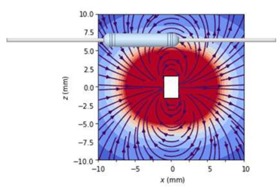

Figure 10. Magnetic field lines compared to the size of the reed switch. Size to scale

This is in contradiction to the PIDO characterization as performed in the Helmholtz coil, which produces a uniform magnetic field. It is assumed that this difference is the main cause for the difference in measured PIDO zone and the initial analysed PIDO zone.

Attempts to adapt the model, such as a calculation of the effective flux over the length of the reed, were unsuccessful. The most pragmatic approach has proven to apply a knock-down or Q-factor on the effective magnetic flux. Unfortunately, this Q-factor is dependent on the reed-magnet combination. For stronger magnets or less sensitive reeds, the point of activation is further away from the magnet where the field lines are more uniform, see figure 11.

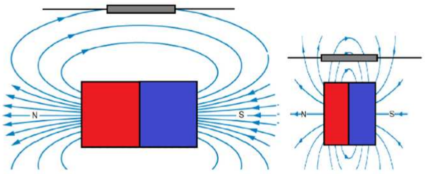

Figure 11. Magnetic field lines for a strong magnet (left) and weak magnet (right)

For this reason, the Q-factor has been empirically determined for every magnet-reed combination. The Q-factor can be determined by measuring the distance between magnet and reed at which the reed is activated. This characterizing is done with the reed perpendicular to the magnet and only changing the distance over one axis. Based on the distance at pull-in, the magnetic flux from the magnet can be derived from the analytical models. The Q-factor is the ratio between the two pull-in values, i.e. from the magnet and from the coil. This factor will be used as a knockdown factor in the analyses model; resulting in updated model results as shown in figure 12.

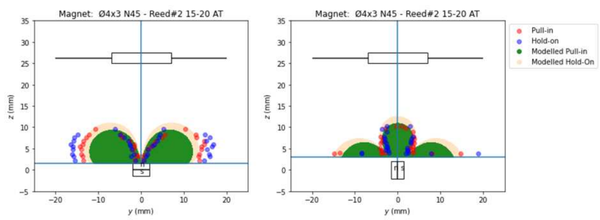

Figure 12. Comparison between measured PIDO zones and analysed zones from the updated model.

With this correlated model, detailed functional analyses can be performed to determine the reed switch behaviour when implemented in a mechanism. The above figures only shows the most common PIDO zones, however detailed scenarios can be analysed or optimized, for instance for more complex trajectories of the magnet with a combined translation and rotation. It should be noted that the results of the analyses model are to be considered as a starting point for the design. It is recommended to always perform a verification and design optimization by test using the actual magnet-reed combination.

4 VERIFICATION TESTING

4.1 Environmental testing

To verify the extended environmental range, the following verification tests have been performed:

- Sine vibration testing
- Thermal Cycling
- Life testing under thermal conditions.
- Radiation testing

Both the reed switch and reed switch assembly have been subjected to vibration testing. 14 RSA's have been subjected to up to 125g's in the range up to 100 Hz. In addition several unmodified reed switches have been subjected to levels of 165g. All of the reed switches functioned accordingly after being subjected vibration levels.

Several reed switches and RSA's have been subjected ambient pressure and thermal vacuum cycling tests have been. The most extreme tests is the test campaign of 3000 cycles of -175°C to +175°C. All of the reed switches functioned accordingly after being subjected to the thermal cycling campaign. Additionally PIDO sensitivity tests are performed at extreme temperatures; this indicated that the PIDO values only change by a few percentages, making it robust for temperature variations.

As part of the thermal cycling tests, a life tests has been performed on six reed switches. A total of 5.1 million reed switch operations have been performed during the 3000 cycles between -175° and +175°C. Hence it has been demonstrated that not only the reed switch is capable of withstanding the extreme thermal conditions, but also can operate extensively under these conditions.

Radiation testing has been performed on several reed switches, with effective doses ranging between 16 Mrad up to 2960Mrad. The operational performance does not seems to be affected by these radiation doses.

4.2 Characterization and Electrical Health Checks

Reed switches delivered by the manufacturer will always undergo a screening and a characterization, however additional testing is required due to the modifications made on the reed leads. These modifications alter the performance of the reed, but might also have an impact on the health of the reed. Additionally, characterization tests and electrical health checks are required to determine any change on the reed after being subjected to the more extreme environmental conditions.

For the characterization and electrical health checks dedicated Helmholtz coils have been developed, see figure 13. Helmholtz coils are used to provide better accessibility to place the test articles in the setup.

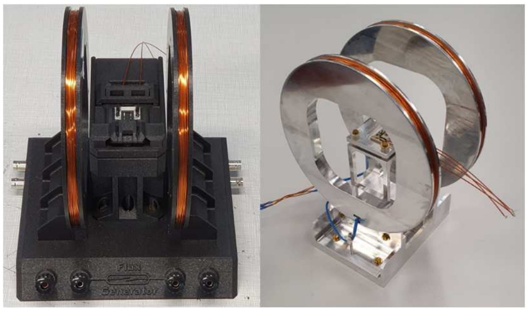

Figure 13. Helmholtz coils for the characterization tests and electrical health checks

To characterize the Pull-in and Drop-out values of the reed switch, the magnetic field generated by the coil is increased and decreased until the reed activates and de-activates. To nullify the Earth's magnetic field, tests are repeated with the magnetic polarity of the coil flipped; when averaging the measurement results of both tests, any external magnetic field is compensated for. Prior to these tests, the reed switch is being magnetically saturated get rid of any magnetic memory in the reed switch, thus leading to more consistent results.

For the electrical health checks of the reed switches, dynamic contact resistance (DCR) measurements are performed as suggested by the manufacturer [5]. DCR measurements determine the change of contact resistance under dynamic conditions. By opening and closing the reed switch with a certain frequency, the resistance across the contact gap will change. This phenomenon, analysed over time, can give indications about the health of the reed.

Schematic information is provided in literature [5], but details are again lacking. The DCR test setup developed at Airbus Netherlands – as shown in figure 14 - consist of

- A Helmholtz coil
- An electrical measurements circuit based on a Wheatstone bridge with the reed switch of the RSA as one of the bridge elements, see figure 15
- Two Delta SM7020-D power supplies, with controllable current and voltage for the Helmholtz coil and measurement circuitry
- An NI Data Acquisition Box (DAQ) for the control of the power supplies and the read-out of the measurement circuit.

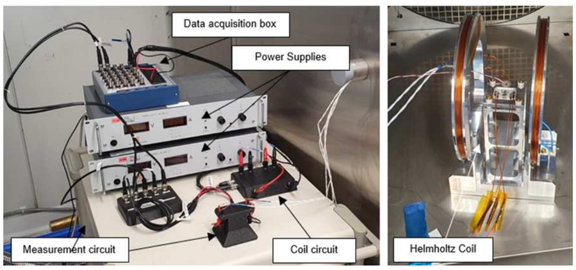

Figure 14. DCR Test setup for reed tests under APTC

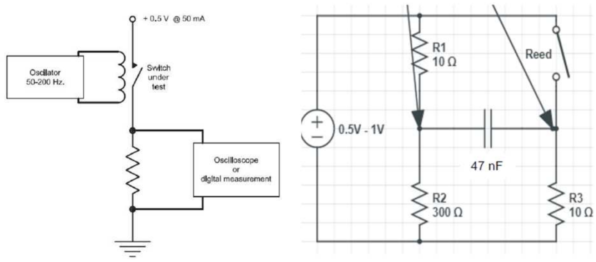

Figure 15. Measurement circuit used for the DCR tests. Proposed by literature [5] (left) used (right)

A comparison between the schematic results for a DCR test as provided by the manufacturer [5] and DCR results as measured by Airbus are shown in figure 16. The measurements shows the overlap of the 50 measurements of the DCR test. Although the shapes of these graphs might look similar, several differences are observed. First of all the operating time is far below the specified 600µs and the indicated graph. Due to this, the DAQ sampling frequency of 2MHz seems to be on the limit what is required for a proper measurements. Secondly, there seems to be a direct transition between reed bouncing and wavering contacts, without any dynamic noise. Thirdly, often a second bounce seems to occur after the wavering contacts have damped out, complicating the processing and interpreting the health by an algorithm.

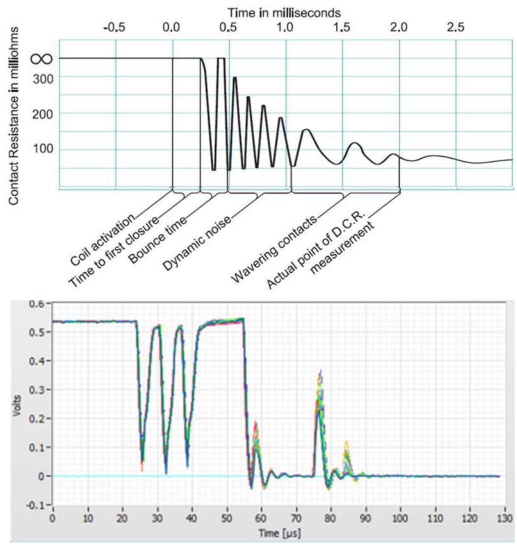

Figure 16. Schematic DCR results [5] (top) and DCR results as measured by Airbus Netherlands (bottom)

The purpose of the DCR tests is to identify defect reed switches after modification and integration in the RSA. A DCR measurement of a reed switch with a broken capsule is shown in figure 17, showing the chaotic behaviour of the different 50 DCR cycles. This indicates a clearly unacceptable reed switch behaviour and can be picked out easily, however in reality, there is a whole variety of responses possible which might or might not indicate a faulty reed switch.

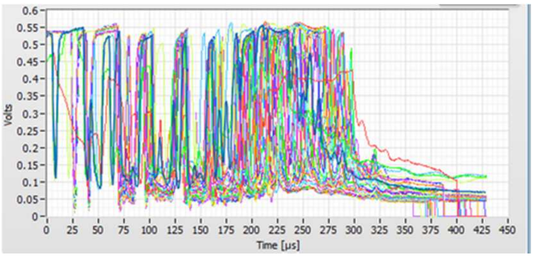

Figure 17. DCR measurements results from a defect RSA

Development of processing algorithms and detailed statistical analyses are ongoing to perform the health screening as part of the test campaign. Momentarily the health of the reed is determined by examining the amplitude-timing relationship of the rebounds. Figure 18 shows a 3-dimensional projection highlighting the principal axes with the most substantial time-amplitude deviation of the DCR measurement. For one of the test articles a significant difference was identified – measured pre- and post APTC – which correctly suggested a defect.

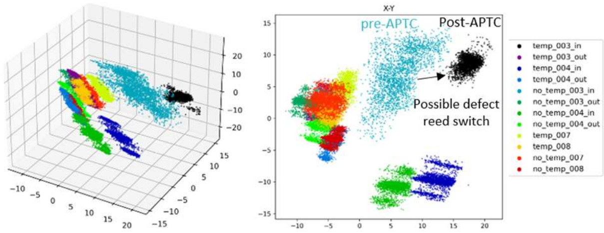

Figure 18. 3-dimensional projection of the most substantial time-amplitude deviation of the DCR test.

4.3 Functional verification testing

Several reed switch assemblies have been included in one of the engineering models of a solar array deployment mechanism currently under development, see figure 19. Functional verification tests showed that all reed switches operated successfully and as intended.

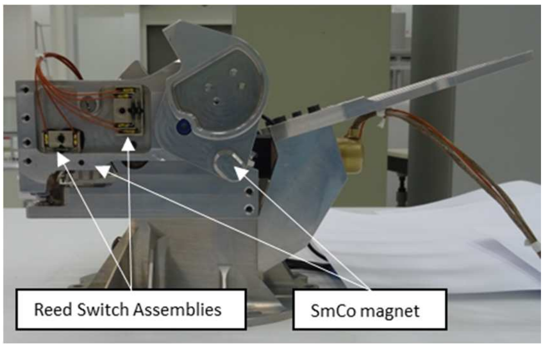

Figure 19. Two RSA's in one of the deployment mechanisms under development at Airbus Netherlands

4.4 Upcoming test campaign

With all performed development activities, Airbus Netherlands is confident of the reed switch performance. Upcoming activities are the batch procurement of the reed switches followed by a qualification test campaign, which is a repetition of earlier performed tests.

5 CONCLUSIONS AND RECOMMENDATION

Based the performed activities, the following conclusions and recommendations can be made:

- The reed switch can be a viable alternative solution for the deployment telemetry. All upsides of the reed switch have proven to be true, while the major challenges – the fragility of the glass tube and the limited environmental specifications – are proven not to be as critical as expected.
- The reed switch is capable of sustaining environmental conditions far beyond what is specified by the manufacturer.
- The functional performance of the reed switch can be modelled using a dipole model for a magnet. Due to the size of the reed switch compared to the curvature of the magnetic field lines, the reed switch does not act as a point sensor. However, by implementation a compensation factor, the analyses can be performed with the reed as a point sensor. This factor has to be determined by tests for every magnet-reed combination.
- Although the functioning of the reed switch can be modelled, it is recommended to always perform a verification and design optimization by test.
- All manufacturing tooling and integration processes of the reed switch assembly have resulted in a stable product. Electrical health testing by means of DCR testing has validated the integrity of the reed switches after the manufacturing and after environmental tests.

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