DESIGN AND TESTING OF A ROLL-RING®
FOR 234 MILLION REVOLUTIONS OF OPERATION IN SPACE

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ABSTRACT

Diamond-Roltran was contracted by Airbus Defence and Space GmbH, Friedrichshafen to deliver a Roll-Ring® Power and Data Transfer Device (PDTD) capable of operating for 234 Million revolutions in space for the MetOp-SG satellite program. The 1075A Roll-Ring transfers power and electrical signals, including Low-Voltage Differential Signaling (LVDS), for the Microwave Imager (MWI) and Ice Cloud Imager (ICI). This paper details the design, manufacturing, and testing of the Roll-Ring which ensures it successfully meets all requirements.

The Roll-Ring uses gold plated rings and flexures (spring-like rolling elements) to transfer electricity through the rotating mechanism instead of using a frictional contact. All life-related design elements were analyzed and tested to ensure that the Roll-Ring will operate for 234 Million revolutions without maintenance. Testing was performed to study the mechanical state of the rolling elements, quality of data transfer, and environmental handling capability. Lessons learned during the design and manufacturing processes will be presented.

DESIGN OF THE 1075A ROLL-RING

The 1075A Roll-Ring is a minimalistic, yet robust design. It uses the same fundamental technology as Roll-Rings that are currently operating on the International Space Station (ISS); where long life and performance capabilities have been proven in the Solar Array Drive Mechanisms and in the PDTD.

The 1075A design is a bearing-less Roll-Ring. The rotor and stator are captured and held concentric by a retention plate. The retention plate is removed during the Airbus Defence and Space GmbH assembly process, while the Roll-Ring utilizes bearings of the scan drive unit to allow for rotation. The Roll-Ring is protected from the outside environment by a contactless labyrinth seal that contains a torture path to particle entry.

There is no need for greases, adhesives, or fluids inside of the Roll-Ring. Because of this, items that could potentially cause mechanical failure are highly limited by design. Other than standard dimensioning and tolerancing, all mechanical design focus can be placed on to three critical items.

1. Flexures:

Flexures are the heart of the Roll-Ring. Flexures are made of a gold-plated spring material and are compressed and retained between inner and outer grooved rings. Flexures have an extremely thin cross-section and as a result, a very low inertia and extreme resistance to movement under shock and vibration. The compression retains the flexures in position while also providing a strong contact force for low resistance.

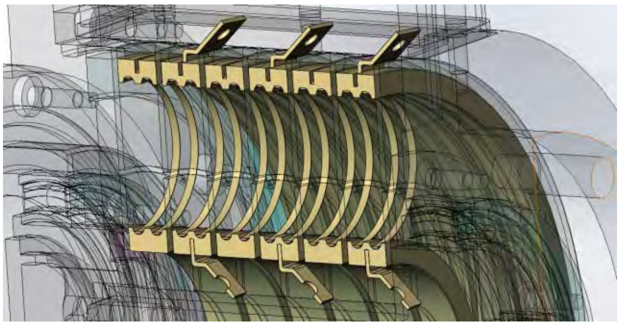

Figure 1: Typical Roll-Ring Cross Section. Shown here is the electrical pathway Terminal → Outer Ring → Flexure → Inner Ring → Terminal, or the reverse.

Both electrical power and signal transfer are improved with lower resistance. For power transfer, reduced resistance means less heat generation and improved efficiency. For signal channels, reduced resistance increases the quality of the transferred signals.

Any out-of-roundness, bump, pit, nodule, or scratch on the rolling contact surface of the flexure can result in increased resistance or noise. This needs to be tightly controlled by design tolerances and inspection.

The life of the flexure can be determined theoretically. One can think of the flexure as undergoing a cyclic spring action as shown in Fig. 2.

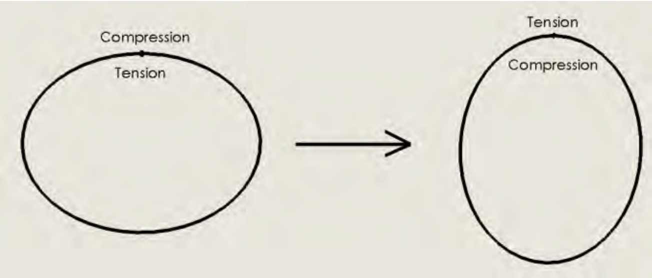

Figure 2: Depiction of the compressed flexure's rolling spring action through 90° of rotation.

From the tolerance stack-up and thermal expansions, maximum and minimum compression and therefore stresses, can be determined and compared with the spring material's Whöler (s-n) curve to find expected fatigue life. Typically, the flexure is found to have cycling stresses below the endurance limit of the material with some safety factor. In such a case, the flexure will theoretically roll forever without failing due to fatigue.

The 1075A design was found, conservatively using fully reversed bending (R= -1) for the calculations, to have an equivalent stress of 180MPa. This stress is far below the endurance limit of the material with a safety factor of 2.2.

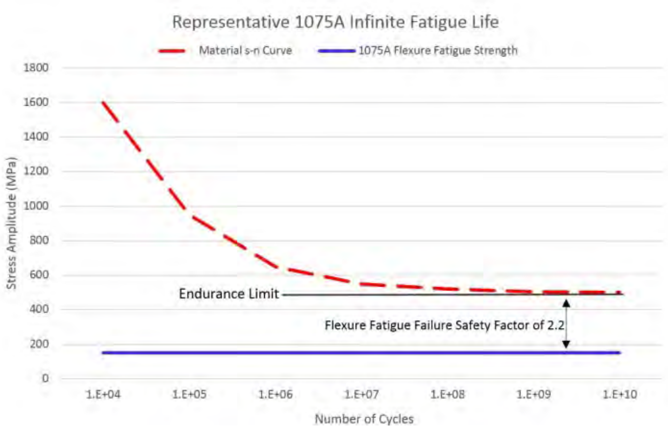

Figure 3: Similar fatigue plot to the 1075A theoretical analysis assuming fully reversed bending.

On the opposite end, when studying the case of a flexure that would not be compressed enough, an increase in resistance or resistance noise could be found. To eliminate this risk, Diamond-Roltran utilized historical data for fit along with proprietary software which assists in calculating the proper contact pressure.

Electrically, the standard 0.75 inch flexure pair in each 1075A channel can carry at least 15 Amps of current by design, which was de-rated to 7.5 amps per channel for a space application. The Airbus requirement is 6 Amps, yielding a substantial safety factor for current carrying capacity.

2. Screws:

Though seemingly a low risk item, a screw which is too loose, or too tight can have catastrophic consequences to the Roll-Ring. On the 1075A, screws apply compression to a spring plate, which compresses an internal spring. This ensures that the inner ring stack and outer ring stacks remain in place.

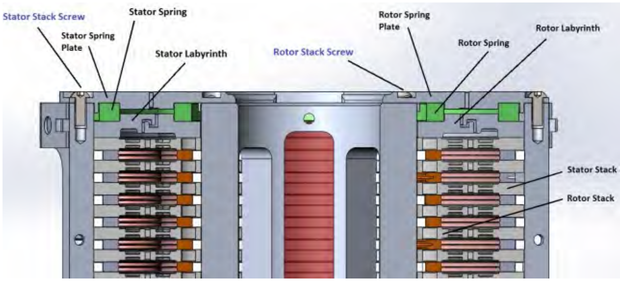

Figure 4: 1075A Rotor and Stator Stack Configuration.

Considering the high limit for screw assembly torque, calculations are performed to ensure all screws have an adequate safety margin of failure due to stress from assembly torque. To ensure that the torque calculations were accurate, a representative sample set of plates and threaded holes was fabricated. Screws were tightened until they failed from stress and these values were recorded.

Considering the opposite case where the screw may be too loose, locking aerospace threaded inserts were used to ensure that the screws could not come loose during launch and operation.

3. Springs:

Multi-turn wave springs are used to compress the 1075A stacks in position and ensure under all circumstances the stacks of rings remain in place.

Over-compressed springs can fail due to stress. Because of this, Diamond-Roltran engineering worked to calculate the maximum stress at maximum compression under worst case conditions for tolerances, thermal changes, and shock. The spring design was then adjusted in an iterative process until the safety factor to failure was found to be sufficient with a maximum spring stress of 171ksi compared to a spring yield strength of 230ksi.

Under-Compressed springs, in the opposite case, can cause loose rings inside of the Roll-Ring. A free body diagram of worst-case launch conditions with expected g-forces on the ring stacks was generated for both the rotor and the stator.

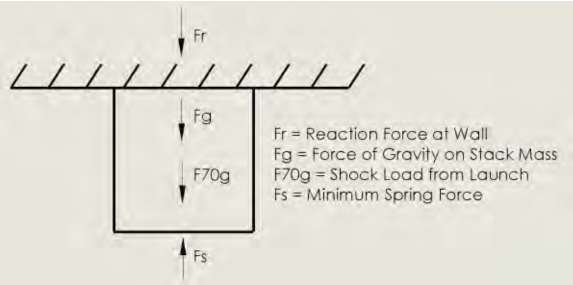

Figure 5: Free body diagram of spring stack at launch.

Using the free body diagram, for the 1075A, it was determined that the spring force will always be larger than all opposing forces with a safety factor of at least 1.375.

CST Microwave Studio Analysis:

CST (Computer Simulation Technology) Microwave Studio was used to analyze the Roll-Ring for LVDS signal transfer capability. Iterative changes in models of physical shape, spacing, and material selection for electrical insulators yielded an optimal combination for LVDS transfer. A breadboard model was manufactured during the preliminary testing for the program and the breadboard model passed all customer requirements for LVDS data transfer.

Redundancy and Reliability:

Redundancies are also designed into the Roll-Ring to reduce risk and improve reliability. Each channel has a redundant channel for the same function if needed. Labyrinth plates are used to create a torture path to prevent any solid contamination into the Roll-Ring and "Full face" insulators are used between channels to prevent migration of contamination.

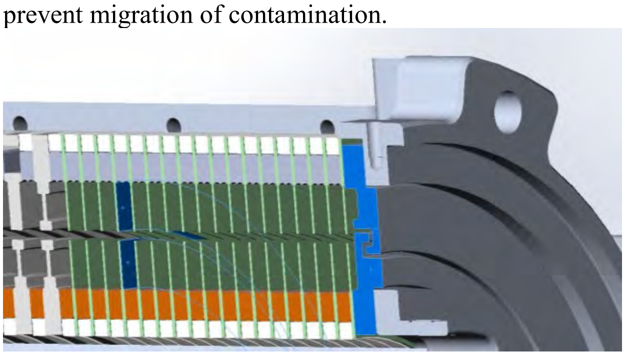

Figure 6: Redundant Labyrinths and Full-Face Insulators Highlighted in Blue.

The Roll-Ring has a dual layer electrical insulation at all points. Combinations of wire jacket, air spacing, shrink tubing, etc. were used at all points to ensure redundant electrical insulation.

The 1075A was designed to require minimal adjustment. The Airbus team ensured that the concentricity of the rotor to the stator was within agreed upon tolerances. All other adjustments are included as part of the dimensions and tolerances of the Roll-Ring design.

MANUFACTURING OF THE 1075A ROLL-RING

As Diamond-Roltran grows in the space industry, continuous improvement and lessons learned will be vital for the success of the Roll-Ring. A few of the lessons learned during manufacturing of the 1075A are described here.

Electrical Wiring Improvements:

Diamond-Roltran's lead lab technician obtained NASA J-STD-001 certification with space addendum as well as being certified as a trainer. All Diamond-Roltran's technicians became certified as well during this program. Initially, soldering quality was not acceptable. After training and soldering new units, Airbus praised the improvement of the soldering as being twice as high quality as before.

Diamond-Roltran also improved processes for wire harness routing, lacing, and wrapping for space applications. After a new training program was implemented, all harnesses assembled were free of shielding errors, had proper shrink tubing, low internal stresses on wire bends and tabs, proper wire bend angles, were secured to the housings appropriately for avoiding possible damage from vibration.

With these two process improvements, the 1075A Roll-Ring's wiring was found to be capable of handling all tested shock, vibration, and thermal vacuum.

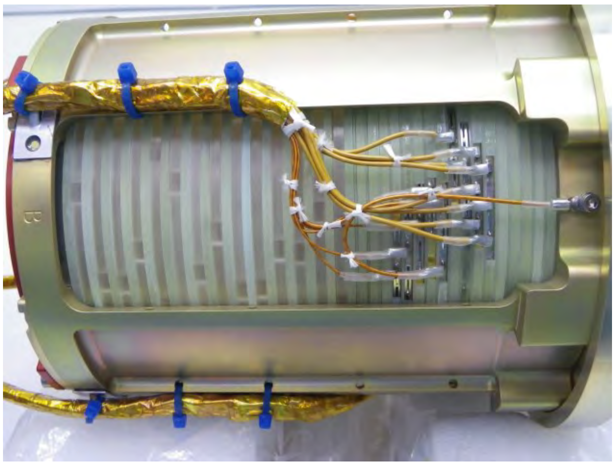

Figure 7: Routed Wire Harnesses on the 1075A Flight Model

Dynamic Resistance Noise Improvement:

To decrease rolling contact resistance and improve noise quality to superior levels, noise plots of the 1075A were studied thoroughly. Dynamic resistance noise plots indicated that there were some particles of dust inside of the early systems. Because of this, a new internal proprietary cleaning process was developed which eliminated the noise. Using a combination of graphical plots, standard deviation, and RMS noise levels, each system shipped was studied and assembled with the least possible resistive noise.

TESTING THE 1075A ROLL-RING

Testing Performed at Diamond-Roltran:

All 1075A Roll-Rings underwent Diamond-Roltran's standard set of electrical tests which include static resistance, operational run-in, dielectric breakdown, Insulation Resistance (IR), and dynamic resistance at maximum operational speed of approximately 47 RPM.

While most of the testing was performed while the Roll-Ring is non-operational, the dynamic resistance is a critical test used to determine the quality of the rolling contact surfaces and electrical connections while the Roll-Ring is operating. A one-amp current is used to power a pair of channels at low voltage. The test for the 1075A is performed at the application's maximum operating speed of 47 RPM. The test station measures resistance 250 times per second for 10 rotations clockwise and 10 rotations counter-clockwise and the data is plotted and recorded in spreadsheet format.

Data for resistive noise is studied using a standard deviation calculation and for nominal resistance levels using an RMS calculation. Plots of the resistance data are also studied graphically and compared to historical data as well. Between the data analysis and graphical observation, it was determined that the rolling contact surfaces were of the highest quality and free of any significant imperfections prior to delivery.

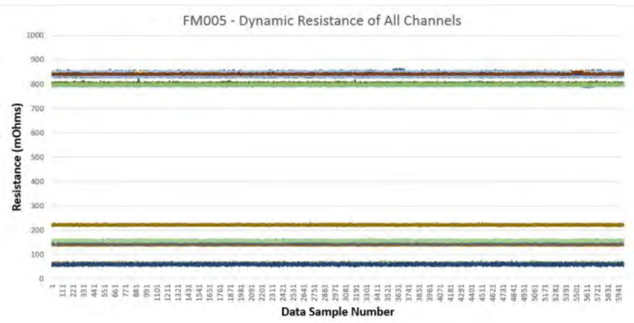

Figure 8: Dynamic resistance plot for all channels of a 1075A roll-Ring.

A Tektronix BitAlyzer 1600 (Tektronix bit analyser) was also used to test LVDS transmission error rate. Bit Error Rate Testing was performed on every 1075A Roll-Ring to ensure the adequate transmission of data was achieved. The 1075A was tested to transmit LVDS signals with 0-bit errors at 120Mbps per channel over 5 minutes. The Airbus requirement was 10-20 times less yielding a substantial safety factor.

Testing at Diamond-Roltran determined that for all units prior to delivery, the insulation systems were sufficient, all connections were in-tact and acting as expected, the rolling surfaces were free of imperfections, and required data transfer rates were achieved.

Testing Performed at Airbus [1]:

After receiving the delivered units, engineers and technicians from the Airbus Defence and Space Mechanism Department in Friedrichshafen tested the Roll-Ring Life Test Model (LTM) extensively at their facility in Germany. Tests performed included:

- Electrical Interface Check
- Function Performance
- Vibration
- Shock
- Release
- Thermal Vacuum (TV) inclusive Functional Performance
- Life Testing

Electrical Interface Check:

An electrical interface check was performed to ensure that the Roll-Ring met all basic electrical requirements. Harnesses were checked for length, proper harness routing and insulation protection. Bonding resistance was measured between the Roll-Ring and bonding studs. DC and AC isolation was checked. Static resistance through all Roll-Ring channels was measured. The Roll-Ring passed all Electrical Interface Check testing.

Function Performance Testing:

Function Performance Testing was performed on each Roll-Ring (Also known as the Power Data Transfer Device or PDTD) channel to ensure signals and power could be transferred with no loss in integrity. It was found that "Signal transfer of power and data has been performed successfully. No signal change can be observed that is caused by power transfer through the PDTD" [1].

Figure 9: LVDS signal transferred through the Roll-Ring at 45RPM and 10 Mbit/s data rate.

Roll-Ring noise test:

It was proven that Rotation of the Roll-Ring did not have a significant effect on noise. Fig. 10 and Fig. 11 show the main power channel at 0 RPM and at 45 RPM. An increase in voltage amplitude of approximately 3mV was observed when the Roll-Ring was operating at 45 RPM.

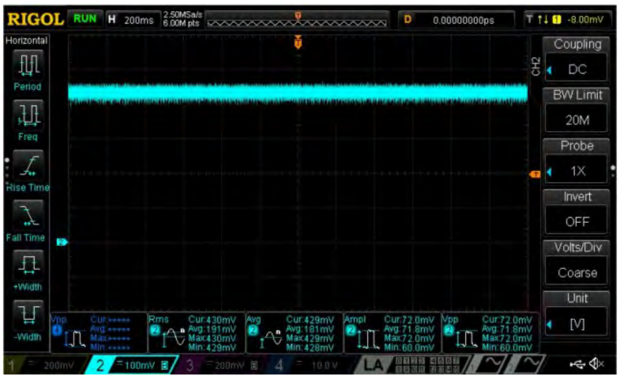

Figure 10: Roll-Ring Noise at 0RPM.

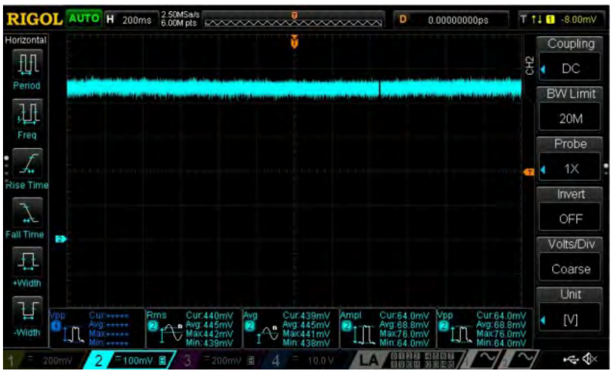

Figure 11: Roll-Ring Noise at 45RPM.

Furthermore, Airbus noted in the final test report that "the Dynamic resistance shall be limited to <15mOhm. This translated to an allowed voltage ripple of 60mVpp@4A or 90mVpp@6A... The observed ripple for all measurements was below 19mVpp" [1].

The Roll-Ring passed all other electrical testing as seen in Tab. 1.

Table 1: Airbus functional Roll-Ring test results. [1]

Description	Req. Value	Meas. Value	Result
PDTD data link (data rate)			
Delay	<5us	<80ns	Pass
Amplitude	<±60mV	±50mV	Pass
Bit Error Rate	<-10-9	<-10-9	Pass
PDTD power voltage drop (two passes)	<0.65V@6A	0.43V@6A	Pass
PDTD power voltage drop (two passes)	<0.5V@5A	0.43V@6A	Pass
Power transfer characteristics			N/A
S/C to IRP Current rating	6A	6A	Pass
SCM transfer through the PDTD power to the IRP	OK	OK	Pass
survival heaters (OFF mode)			
Data Transfer through the PDTD	>=5 Mbit/s	10 Mbit/s	Pass
SCM transfer through the PDTD analog signal from the IRP thermistors to the S/C	OK	OK	Pass

Vibration and Shock:

Eighty-Four different vibration profiles were run on the Roll-Ring as part of a larger system level test. No non-conformances were found.

Shock was also tested with varying ranges of frequency from 100Hz to 10,000Hz and accelerations of g-force from 20g to 1000g. All functional testing was performed successfully after shock and vibration testing.

Thermal Vacuum (TV):

The Roll-Ring, installed in a larger test assembly, underwent thermal vacuum cycling for approximately 300 total hours. The system was cycled 8 times, with Roll-Ring temperatures between -45°C to + 47°C and between approximately 4 x 10^{-6} hPa and 1 x 10^{-5} hPa. A full functional test of the Roll-Ring was performed at peak hot and peak cold temperature on the first and last cycles. Voltage amplitude variation, noise, signal delay, and Bit Error rate at 10Mbps were all confirmed to function normally. No Roll-Ring non-conformances were found.

Life Testing:

The LTM Roll-Ring is currently undergoing life testing under vacuum at the Airbus facility. The unit is currently in the second part of this life test. It has passed the equivalent operational speed portion of the test and is now in the second part of testing during which it is operating at an accelerated RPM. The life test is confirming that the Roll-Ring is capable of handling 234 Million Revolutions of operation. It is currently at 190 Million revolutions, covering a nominal number of in-orbit revolutions of about 177 Million.

Conclusion:

Working with Airbus to ensure that 234 million Roll-Ring revolutions in space is achievable, all aspects of design, manufacturing, and testing of the 1075A needed to be fully studied and understood.

The design of the bearing-less 1075A Roll-Ring is robust with very few areas of concern. Mechanical design consideration can be focussed on just three critical design aspects consisting of flexures, springs, and screws. While performance is ensured through appropriate theoretical modelling, safety factors, redundancy, and designed-in reliability.

In manufacturing of the 1075A, there were many lessons learned that helped to ensure success of the product including noise reduction methods, soldering improvements, and knowledge of wire harness routing for space.

Testing at both Diamond-Roltran and Airbus was extremely thorough and comprehensive. The Roll-Ring passed all testing to date with one test remaining, a life test currently at 190 million revolutions out of a planned total of 234 million.

REFERENCES

1. Airbus Defence and Space GmbH, Friedrichshafen (2019) internal proprietary documentation. Friedrichshafen, Germany.
2. Diamond-Roltran internal proprietary documentation. (2019) Littleton, MA USA.