BRUSHLESS SLIPRING FOR HIGH POWER TRANSMISSION

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ABSTRACT

Honeybee Robotics Spacecraft Mechanisms Corporation (Honeybee) has developed a brushless slipring (the Rolling Contact Connector, or RCC), which has demonstrated the ability to outperform traditional rotary signal transfer solutions in power density and operational life.

Efficient, reliable, high-quality transfer of electrical power has been a goal in the design of spacecraft mechanisms since the inception of the first artificial satellites. Slip rings, and to a lesser extent twist capsules, have served this purpose for decades, however, little has been done to advance the technology in radical, fieldable ways. The intrinsic sliding friction of the slip ring contact interface, increases parasitic torque and inevitably leads to performance degradation and shortened operational life. These issues are magnified in high power slip ring designs, which utilize additional brushes and increased inter-contact preloads.

RCC technology is robust, enabling high power and sensitive data signal transfer; and flexible, possessing the ability to merge with existing slip ring technology to form hybridized rotary signal transfer solutions. In this paper, we present an overview of the RCC technology, developed and patented by Honeybee, and present electrical and mechanical figures of merit obtained through research and experimentation.

1. BACKGROUND

It is common for robotic or mechanical systems to incorporate some sort of rotating interface; and more often than not, electrical power and/or data are required to pass across that interface. Currently available electrical transfer technology includes: slip rings, twist capsules, and flexible service loops; each of which has its benefits and down-falls. Twist capsules and service loops are limited in rotation and cannot support continuous 360° movement. They also have a relatively large parasitic torque associated with their operation. Slip ring technology is limited to the mechanism by which it works. It relies on some combination of stationary brushes and a rotating shaft. The brushes contact the shaft on conductive rings separated by a dielectric. The downfall of a slip ring lies in the sliding contact between the brushes and the rotor. Sliding friction requires some form of lubrication and causes component wear and debris generation [1]. Sliding contacts also suffer from a stick-slip motion profile, particularly at low speed operation. The stick-slip behaviour results in inconsistent parasitic torque and inter-contact conductivity. These sliding contact induced effects reduce the operational lifetime of a slip ring, as well as increase the noise present on data channels. In addition, slipring performance can be degraded due to excessive vibration. Honeybee's Rolling Contact Connector (RCC) technology eliminates each of these limitations.

RCC technology is centered on the concept of using a rolling contact interface to transmit electrical signals. A typical RCC signal path is configured similarly to a planetary gearhead and contains three major components; the inner ring, flexible planets, and the outer ring (Fig. 1).

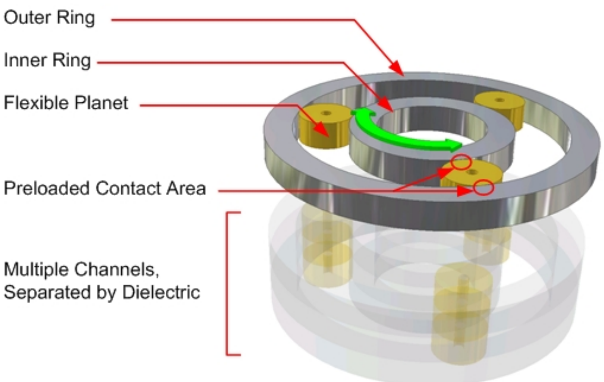

Figure 1: RCC Basic Geometry

Flexible planets are preloaded between the inner and outer rings, and provide the electrical pathway from the stationary to the rotational members. As the RCC inner ring rotates, a planet carrier assembly guides the flexible planets to roll along the outer circumference of the inner ring and the inner circumference of the outer ring. RCC units operate with a pure rolling contact; eliminating any sliding friction and greatly reducing the parasitic torque associated with slip rings and twist capsules. The

Proc. '13th European Space Mechanisms and Tribology Symposium – ESMATS 2009', Vienna, Austria
23–25 September 2009 (ESA SP-670, July 2009)

rolling contact avoids the stick-slip behaviour associated with traditional sliding contacts, allowing for a more constant torque profile throughout operation. The preload at the contact surface provides a low and consistent inter-contact resistance, as well as increased tolerance to vibration and thermal gradients.

RCC technology is flexible in its applications. Designs can be scaled in size to accommodate a large inner ring through-bore, or given additional planets for increased current capacity. These changes can be implemented while maintaining superior electrical and mechanical performance.

2. DESIGN

An RCC unit consists of three primary components including the inner ring, outer ring, and flexible planets (Fig. 2). The planets are tied together with a planet carrier that fixes planet shafts angularly around the axis of revolution. This ensures that neighbouring planets on a single channel do not migrate and make contact. Bearings are used to allow for co-rotation of the inner ring, planet carrier, and planet shafts. Labyrinth seals are used to minimize bearing lubricant migration while maintaining a very low parasitic torque.

Figure 2. RCC Subassemblies (Dimensions: 4” height x 4.5” diameter)

There are multiple design variables that allow for the optimization of an RCC unit for a particular set of requirements, including planet preload, contact geometry, surface finish, and plating selection. These variables are defined to fulfil the requirements set and to minimize inter-contact resistance and maximize operational life.

Electrical contact base materials and plating matrices were selected with the intention of maximizing the performance of RCC devices. To increase endurance strength and operational life, a high strength beryllium copper alloy was selected as the base material for flexible planets. Due to its superior conductivity to weight ratio, an aluminium alloy was selected as the base material for ring contacts. Two unique plating matrices were chosen for RCC electrical contacts. The base layer of non-magnetic electroless nickel (EN) is the same for both plating matrices. This EN layer serves as a diffusion barrier between the gold surface plating and copper in the base metal; minimizing the ability of copper-oxide to form on the planet surface. Surface oxides alter the inter-contact resistance, and decrease overall electrical performance. Gold alloy was chosen as the surface plating due to its low resistivity. The flexible planets experience more wear cycles than the ring contacts, so a harder gold alloy was chosen for its plating matrix. A softer gold alloy was chosen for the rings. The soft gold alloy allows for controlled deformation along the conductive pathway (Fig. 3); improving contact surface finish and noise performance after and initial run-in period. The lines within the lustrous region of the outer ring (Fig. 3) represent the discrepancy between apparent contact area and actual load bearing contact area and are only a small fraction of the apparent contact area.

Figure 3: Contact surface finish after 3 million revolutions. The load bearing contact area has been deformed to a smooth, lustrous finish resulting in a more uniform contact interface.

2.1. Scalability

Concerning standard high power signal transmission, RCC mechanical and electrical performance remains consistent after an increase or decrease in scale. High speed data signal transmissions offer an exception. Data signal transmissions are limited by an upper bound frequency due to signal path length difference (Fig. 4a). This difference has the potential to result in partial or complete destructive interference (Fig. 4b). Larger RCC devices will have a lower maximum data transmission frequency compared to similar, smaller devices. This behaviour is common to slip rings and other continuously rotating electrical interfaces.

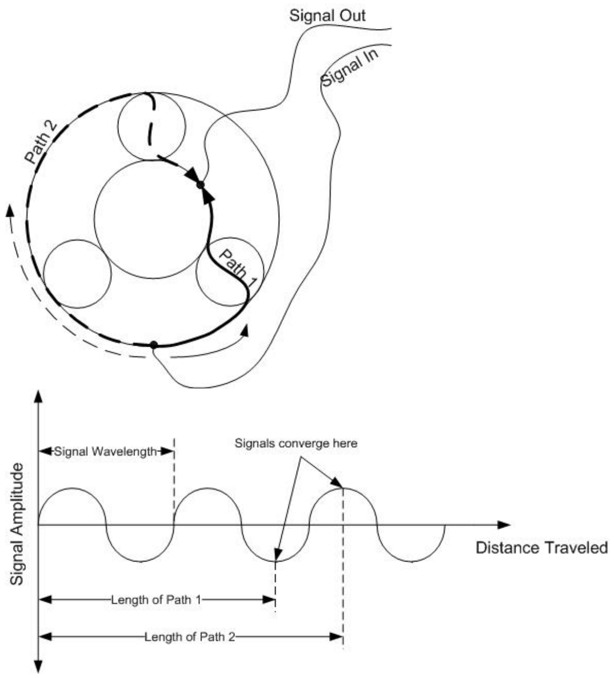

Figure 4a. Signal Path Length Difference (Top)
Figure 4b. Destructive Interference (Bottom)

Frictional heating, and increased parasitic torque losses, often contribute negative effects to the operation of large scale slip rings; potentially precluding operation at high speeds. RCC units will be far less susceptible to these high speed effects due to the lack of sliding friction in the rolling contact.

Increases in RCC power density are possible while maintaining other performance metrics. The current carrying capacity of rolling contact technology is determined by the maximum steady state temperature increase resulting from resistive heating (I^2R heating). This resistive heating can be decreased by increasing the number of flexible planets per channel. Increasing the number of planets adds more pathways for the transmitted current and generated heat to travel. A similar technique is often used to increase the current capacity of slip rings. However, adding brushes to slip ring channels increases parasitic torque and frictional losses, decreasing overall efficiency. Another deficiency of the slip ring concerns the poor distribution of heat generated at the brush-ring contact interface. The brush is continuously subjected to I^2R inter-contact heating, resulting in a local maximum steady state temperature increase.

2.2. Operational Life

Due to the lack of sliding friction, rolling contacts do not wear significantly during operation. Furthermore, Honeybee has implemented custom plating matrices for RCC contacts to maximize operational life and improve noise performance. The outermost layer of the plating matrices consists of two different types of gold. Gold plating was selected primarily due to its resistance to oxidization and excellent conductivity. There is an added benefit to gold plating RCC electrical contacts. The high preload, intrinsic to RCC technology, serves to flatten the relatively soft gold layer during operation, resulting in a lustrous finish (Fig. 3). Due, in part, to the improved surface finish, RCC devices have been observed to improve in noise performance as operation time increases.

Flexible planet geometry has been carefully selected to minimize operating stresses and maximize life. Geometries have been verified by correlating prototype test data to theoretical models.

3. EXPERIMENTATION

3.1. Test Plan

Based on the geometric structure and application of the RCC, it can most often be considered as a simple electrical connector. In cases where high frequency signals are transmitted; it should be considered as both a connector and a transmission line. Any signal carrying conductor can be considered a transmission line once the signal path becomes long relative to the speed and frequency of signal propagation. In this situation the voltage levels at one end of the conductor are noticeably different from those at the other [2]. For an electrical connector it is assumed that the signal voltage levels remain the same throughout, and the voltage change is insignificant. The types of testing performed on the RCC designs were similar to those that are necessary to electrically characterize a connector and a transmission line.

Many of the tests for electrical connector figures of merit were derived from the US Military Standard, MIL-STD-202G Test Method Standard-Electronic and Electric Component Parts [3], including:

- Dielectric withstanding voltage (Method 301)
- Insulation resistance (Method 302)
- DC resistance (Method 303A)
- Resistance temperature characteristic (Method 304)
- Capacitance (Method 305A)
- Quality factor (Method 306)
- Contact resistance (Method 307)

Additional tests were required to characterize the RCC due to its slip ring style operation, and transmission line behaviour at high frequencies. Tests were developed to determine parasitic torque, resistance deviation (also referred to as noise), impedance, transmitted data signal integrity, and inductance through the RCC signal path.

A life test was performed on an RCC test unit to determine the operational life, and to measure the effects of extended operation on resistance deviation.

3.2. Test Results

Data acquired from testing and analysis allowed Honeybee to define the performance of an RCC device.

3.2.1. Parasitic Torque

Parasitic torque results were consistent with RCC design expectations. The lack of sliding friction in RCC devices allowed for extremely low parasitic torque, and the prevention of stick-slip behaviour. The torque profile at low speed operation was stable (Fig. 5). Experimental values for parasitic torque ranged from 30 to 70 mNm on tested RCC devices.

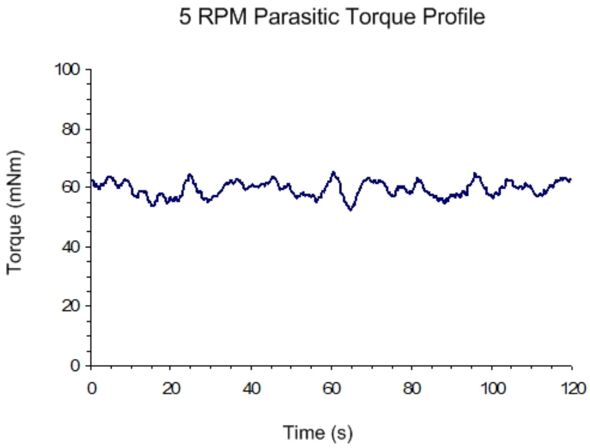

Figure 5: RCC Parasitic Torque Profile at 5 RPM Operation. Because RCC technology does not rely on a sliding rotary interface, RCC devices avoid the stick-slip behaviour common to slip rings. This trend is evident in the experimental parasitic torque data.

3.2.2. Inter-contact Resistance

Inter-contact resistance testing indicated a strong relationship between preload and inter-contact resistance. A typical experimental value for RCC inter-contact resistance is in the range of 0.8 to 1.2 mΩ. Theoretical values for contact resistance were often within the range of 1-2% of experimental values. These results were expected because the theoretical inter-contact resistance was determined using the apparent inter-contact area. The metallic contact area (also referred to as a-spots or asperities), where transmitted current experiences no perceptible resistance, is typically a small fraction of the theoretical or apparent contact area [4]. Further analysis revealed an accelerated increase in inter-contact resistance below a preload of 0.6 lbs. Misalignments between contacts were observed at low preloads which reduced the apparent contact area. It is also suspected that the lower preloads were unable to displace surface contaminations (oxide layers, organic films), reducing metallic contact area.

3.2.3. Transmission Line

Tests for typical transmission line electrical figures of merit were grouped together into one test program. Values for channel inductance, resistance, and impedance, and inter-channel capacitance were output. Steps were taken to reduce the contribution of the RCC device I/O leads in the circuit analysis results. On average, the inter-channel capacitance was less than 0.07 pF. Average values for channel resistance and inductance were found to be less than 1 mΩ and 0.065 mH, respectively. A trend of impedance vs. frequency for the RCC is presented in Fig. 6. At a test frequency of 1 MHz, the series impedance was observed to be under 0.5 Ω. The impedance of an RCC device varies linearly with frequency once the contribution from the imaginary component begins to exceed the DC resistance.

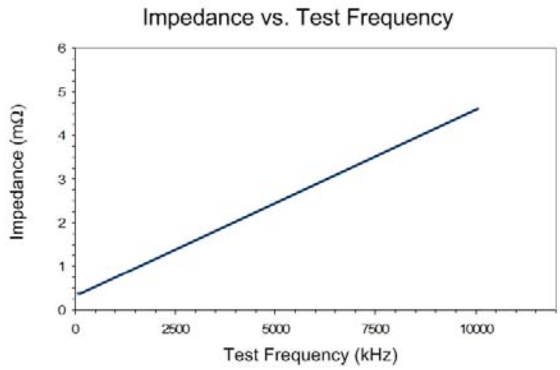

Figure 6: Three Planet RCC Series Impedance vs. Test Frequency. At 1 MHz, the series impedance was found to be less than 0.5 Ω, indicating the ability of RCC devices to transmit analog signals with higher frequency components.

3.2.4. Current Capacity

Current capacity is a critically important figure of merit for any rotary power transfer device. In order to characterize the current capacity of the RCC, thermocouples were embedded in ring contacts to quantify the temperature changes from inter-contact I^2R heat sources. Quantifying the steady-state temperature increase from ambient test temperature is an excellent indicator of performance at high current loads. A typical trend of ring temperature vs. time is presented in Fig. 7.

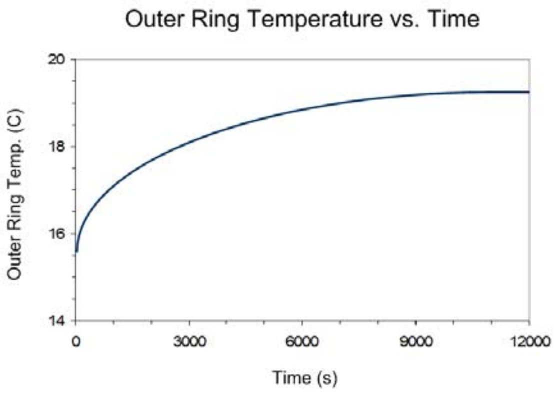

Figure 7: Outer Ring Temperature vs. Time, 0 RPM Operation, 20 A Transmitted Current.

DC currents from 0 A to 20 A, at rotational rates of 0, 30, and 60 RPM were used during the test. The current capacity tests were performed in an ambient environment inside of an enclosed chamber. Data was collected before current was applied to ascertain the room temperature, and the test was manually ended once the ring temperature stabilized. The maximum increase in temperature, of 21°C, was recorded on the inner ring thermocouple during a 20 Amp, 0 RPM test. Results from this series of tests (Fig. 8) indicate the ability of the tested RCC device to transmit significantly higher currents than those tested. The test results also indicate improved performance with increased operational speed.

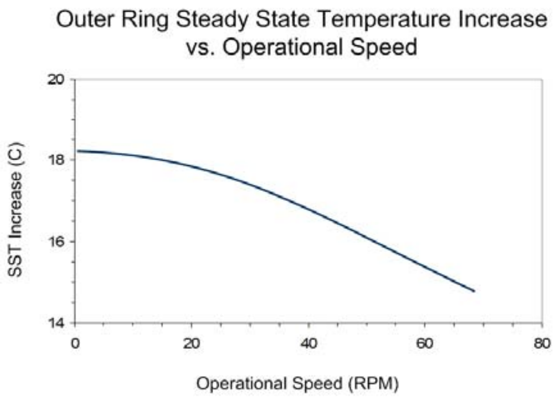

Figure 8: Outer Ring Steady State Temperature Increase vs. Operational Speed. Results from the series of current capacity tests indicate the ability of compact RCC devices to transmit significantly more current than 20 A per channel.

3.2.5. High Potential

In order to further characterize the power transfer capabilities of RCC technology, a high potential test program was executed. This program included tests for insulation resistance, and AC and DC dielectric withstanding voltage. Out of a series of tests, the minimum values for AC and DC dielectric withstanding voltage were found to be 2000 ACV and 3000 DCV, respectively. The minimum experimental insulation resistance was 700 M Ω. It is possible to improve these results with minor modifications.

3.2.6. Communication

Transferred data signal integrity is another important characteristic for rotary signal transfer devices. This characteristic was evaluated through two types of tests; a signal jitter analysis, and a bit error rate test. For the jitter analysis test program, M-LVDS and RS-485 digital signals were passed through an RCC while operating at rates of 0 and 30 RPM. A data rate of 2.5 Mbps was chosen for the experiment. A minimum of 2.25 billion edge transitions were captured to form an eye pattern suitable for jitter analysis (Fig. 9). Analysis of the eye patterns revealed a minimum eye opening of 97.5%, corresponding to a jitter percentage of 2.5%. The low jitter value indicates the ability of the RCC to transmit digital signals at data rates exceeding 2.5 Mbps.

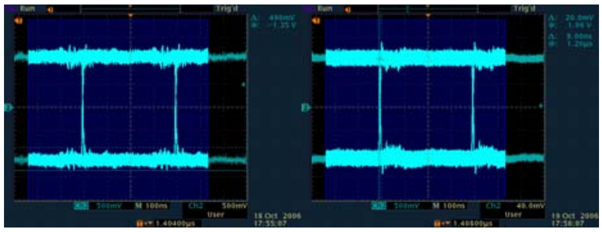

Figure 9: Eye Patterns: Left - RS-485 Control Case, Right - RS-485 30 RPM Operation. Communications testing demonstrated the ability of RCC technology to flawlessly transmit RS-485, M-LVDS, and MIL-STD-1553 at data rates up to 2.5 Mbps.

The MIL-STD-1553 communication standard was used to evaluate bit error rate performance. Several tests were performed on the RCC at operational speeds of 0, 10, and 30 RPM, and at a data rate of 2 Mbps. Zero bit errors were recorded throughout the suite of tests, after transferring a total of 86.4 billion bits through the RCC.

3.2.7. Operational Life

Operational life is of critical importance to slip rings and other rotary signal transfer devices. In order to determine operational life, the RCC was run continuously for an extended period of time with regularly scheduled functional tests. The functional tests comprised of resistance deviation analyses for all channel pairs. Noise or resistance deviation test results are used as a non-invasive indicator for contact wear and are a standard figure of merit for slip ring devices.

Currently, operational test data is available for over 16 million revolutions (Fig. 10).

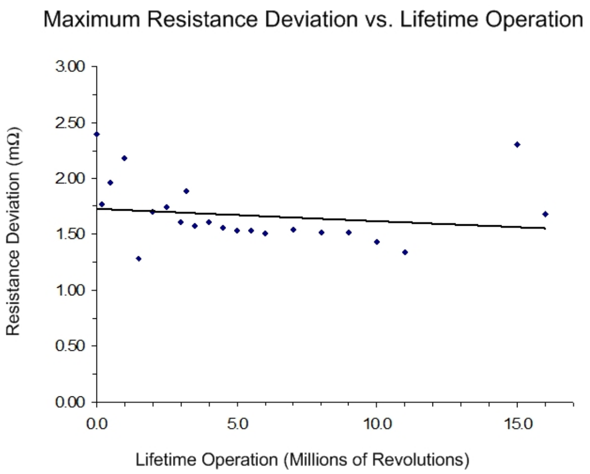

Figure 10: Operational Life Noise Performance Trend. Maximum resistance deviation was observed to trend downward with prolonged continuous operation. Note that the increase in resistance deviation at 15 million revolutions was due to an extended period of in-operation; allowing contaminants to form on the contact surface. Following a second run in period, resistance deviation returned to nominal levels.

4. CONCLUSIONS

Experimentation on RCC designs revealed exceptional parasitic torque results, electrical noise characteristics, current carrying capacity, and operational life. The maximum temperature increase of 21°C, recorded in the 20A current capacity test, indicates the ability of compact RCC devices to transfer currents well above 20A without issue. Adding more planets to an RCC channel will further increase current carrying capacity and power density while maintaining a low parasitic torque.

The RCC has continued to perform well through 16 million revolutions. Resistance deviation has remained in the 2 mΩ range. Life testing is on-going.

The theoretical and experimental performance of RCC technology make it an excellent candidate as either a stand alone, or slip-ring hybrid solution for high power and long life applications such as SADAs and satellite power return rings.

5. REFERENCES

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