A NOVEL CONTACTLESS INDUCTIVE AND CAPACITIVE ROTARY JOINT FOR POWER AND SIGNAL TRANSMISSION

Dan Mirescu [1], Mickael Tuffery [2], Frédéric Lacour [2], Jean-Bernard Mondier [3]

[1]*EXXELIA SAS, Illange, France.*

[2]*EXXELIA SAS, Chanteloup en Brie, France,*

[3]*CNES, 18 avenue Edouard Belin 31401 Toulouse Cedex 9 France, jean-bernard.mondier@cnes.fr*

INTRODUCTION

Some rotating mechanisms, either for Space, ground or airborne systems, require to transfer the electrical power and data while performing a continuous rotation at tens of turn per minute with a life profile which can reach several hundred million revolutions. In space mechanisms, such needs are notably relevant to instruments like radiometers or scanning mechanisms. Good examples are the MWI and ICI instruments for the satellite METOP of the 2nd generation. Such instruments generally use electrical slip-rings collector. However, in slip-rings, the electrical data is transferred by using conductive brushes and rings. Whatever the materials, coating, lubrication and techniques used to increase the lifetime, such systems are subjected to a mechanical wear which, eventually brings an unacceptable degradation of performance. Moreover, a slip-rings collector is not likely to run properly over a 200 million cycle mission or more as required by such instruments.

In order to overcome this problem, contactless technologies have been developed that can transfer electrical signal, either power and data. The French Space Agency CNES has been developing a CTSC (contactless electrical transfer device) through several research activities. The last step dates from 2012 with the realization of an engineering model which comprises a rotating transformer for power transfer and capacitive components for signals' transmission. Functional electrical tests carried out at the laboratory confirmed the expected performances already recorded with the previous models.

The current development phase is performed by EXXELIA with CNES funding. It aims to make a space mission demonstrator. The main development difficulty was to meet the electrical performance objectives, which in that kind of design require very tight functional clearances, while complying with the space mechanisms operational requirements, notably the mechanical and thermal environments. A qualification model has been designed, manufactured and integrated. It is currently undergoing its qualification test sequence. The preliminary test results are presented in the paper. In parallel with the development of the CTSC's mechanical part, an electronics has been developed by the company STEEL, also under CNES funding. This device splits into two upstream and downstream units whose role are to work out the input and output electric signals. A coupling between the three units was carried out in order to validate the global performances of the CTSC.

MAIN RESULTS FROM THE PREVIOUS STUDIES

The starting point of this development was to find a technical solution to limit the drawbacks of existing slip-rings collector's wear, their relevant particular generation and the inevitable limitation of this kind of device performance. Another critical requirement was to ease the qualification tests which normally require to run the assembly over a large number of turns to demonstrate its capability to perform the mission, owing that the good expected result is not always granted. The mitigation of such risks was at the centre of the CNES's concerns.

The study of multiple options led us to a selection of a contactless transfer device fitted with an inductive module for the power and a capacitive module for the signals. The discarding of all contact and wear is at the expense of using two electronic cards, upstream and downstream to the unit, to process the electrical signals.

This design allows to transfer the entire DC power bus through the rotating joint. It simplifies the power transfer management in such a wat that it removes the need to determine how many lines should be designed and provided for a given instrument.

The selected design for the signal module, without any frequency carrier, nor modulation, was based on a direct coding of the digital signal which removes its continuous part, not transferable. The signal transfer module features a digital code based on the Manchester's code. This is a classical design in data digital transfers likewise in the 1553 digital bus.

The latest manufactured and tested prototype is shown in the following picture. It is fitted with an inverter-type transformer and two capacitive differential channels.

Figure 1: CNES prototype contactless device

The contactless device prototype comprises a ball bearing assembly to provide the rotor's rotation guidance. This option was deemed necessary to get a controlled air-gap in each module, a condition to perform all the electrical tests. However, it was deemed that fitting the future flight device with its own friction bearing would have greatly reduce its appeal. Such a friction bearing would have brought about a difficult and time-dependent additional qualification sequence which is contrary to the contactless design philosophy.

Power transfer module

It was designed with an inverter which runs at a 100 kHz frequency. The following plot shows the main performance of the power module. It displays the level of transfer efficiency performed as a function of transferred power for 2 magnetic induction options and 3 levels of input voltages. We can see that to get an efficiency above 0.9, the minimum input voltage is rated by the targeted power.

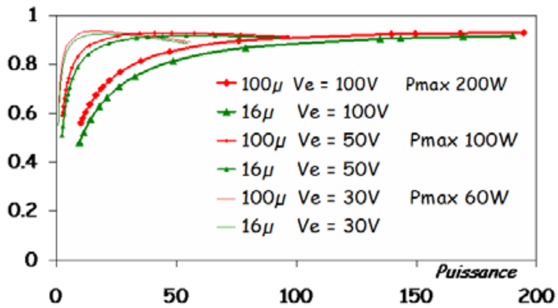


Figure 2: CNES prototype power transmission efficiency

Signal transfer module

Each signal transmission comprised 2 differential analogue channels fitted with an input and output driver, which allows to remove all electromagnetic disturbances. Coding and decoding units were added at each end of the lines. The main performances of this design is an overall gain of 0.5 up to 10 MHz, at a flow rate of 1 Gbps with a cross talk between 2 neighbouring tracks higher than a 32 dB margin.

MAIN REQUIREMENTS

The main CTSC requirements are as follows:

- a power transmission through an inductive part which shall perform 60W for an input voltage of Vi=30V, 100W for Vi=50V and 250W for Vi=100V.
- a signal transmission which shall be compliant with rates of 5Mbps at 10MHz or 11Mbps at 20MHz through 2 capacitive differential channels.
- a bearing's assembly which allows a full range rotation only for testing purpose not flight.
- Length < 129 mm.
- External diameter < Ø98.
- Friction Torque < 0,01 Nm.
- Total mass of the CTSC < 1kg.
- Temperature Range: -40°C to +80°C.

DESIGN DESCRIPTION

The development of a dedicated bearing assembly within the CTSC turned out not to be in line with the development's objectives. It turned out to be more logical to rely on the host instrument's main bearing mechanism which should be designed with a specific lubrication and qualified relatively to its own mission need. Consequently, one CTSC strong design driver was that the future flight model does not include its own bearing assembly. Nevertheless, the CTSC demonstrator is supported by a bearing tool which simulate and also specifies the instrument main bearing performance requirements.

The CNES prototype is at TRL 4. The two main purposes of the EXXELIA demonstrator is to reach a TRL 6 and to industrialize the product.

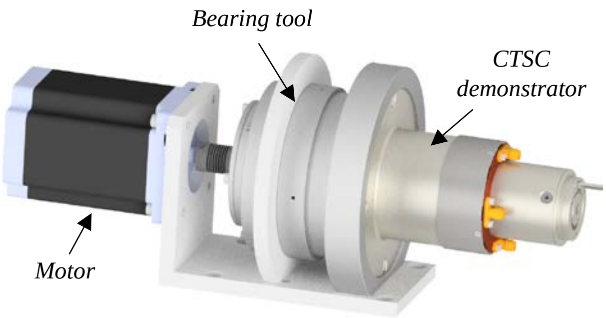


Figure 3 : demonstrator with bearing tool and motor

Mechanical design of the rotary Joint

The bearing less rotary joint developed by EXXELIA is made up of two modules:

-a capacitive module to supply two signal channels and one shielding channel: 5 brass rings separated by 4 insulating rings.

-an inductive module to supply one power channel: two ferrite pieces equipped with windings.

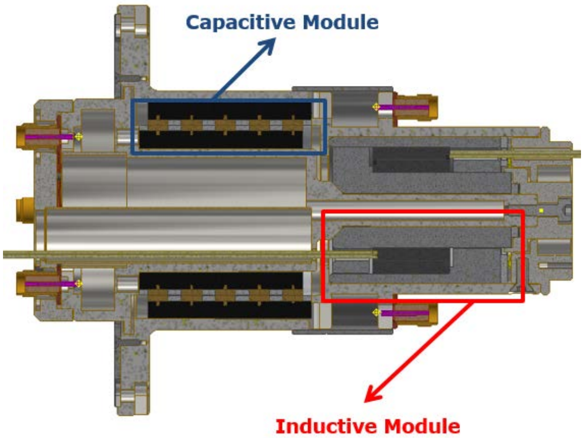


Figure 4 : Cross Section of the demonstrator

For each module, the key feature of the mechanical design is the functional air gap between rotor and stator. This dimension must be as small as possible to maximize transmission performances.

To ensure and to maintain an optimal air gap without any risk of damage (shocks between rotor and stator), several mechanical and thermal parameters from the specification have been taken into consideration in the rotary join design:

-the tolerances of all the mechanical parts induce geometrical dispersions, so it was necessary to limit the number of parts and to specify tight tolerances.

-a cantilever assembly into the host mechanism: this type of assembly facilitates the rotary joint integration, but it is detrimental to the main function of the rotary joint.

-the total length of the rotary joint: this parameter increases the radial displacements during rotation.

-a rotary joint in a bearing less configuration (called pancake configuration). As the rotor is free in the stator, some precautions have been integrated in the design to secure the rotor position relative to the stator position.

-the stiffness of the host instrument's main bearing mechanism which induces an angle tilt.

-the temperature range generates geometrical variations due to thermal expansion.

-the mechanical loads taken from a space life cycle: air gap must be maintained in spite of the displacements due to the random vibrations and the mechanical shocks.

The complete assembly made up of the rotary joint and the bearing tool has been modelled and simulated with RBSDYN software. This software developed by the CNES calculates the radial displacements from the rotor and the stator taking into account the bearing tool stiffness. Whatever the combination of the load case (temperature, vibration, mechanical shocks, …), this displacement must be smaller than the functional air gap to ensure the product integrity.

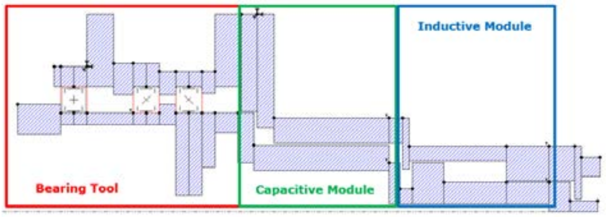


Figure 5: Modelling with RBSDYN

Finally, for a bearing less rotary joint with a such optimized air gap, a jig tool was necessary during transportation and storage to keep the system in an operation position and to prevent rotor movement relative to stator.

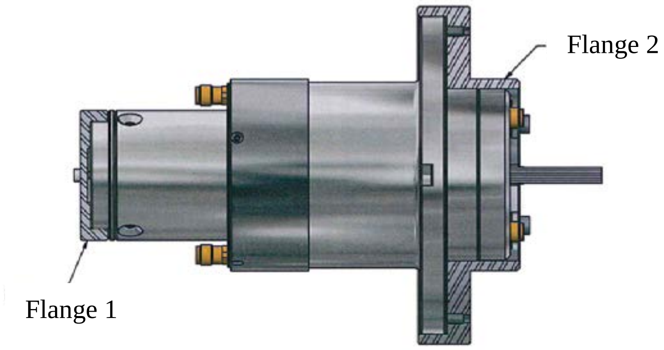


Figure 6: Jig tool: two flanges

Magnetic part of the contactless rotary joint

The magnetic part is in fact a rotating transformer with a primary coil assembled inside a cylindrical L-shape ferrite and a secondary coil fixed outside another rotating L-shape ferrite. The two L-shape ferrites are assembled head to tail with the coils inside the ferrites and define two cylindrical gap areas. The two gap areas allow the rotor to turn frictionless, but will decrease the coupling factor between the primary and the secondary coil. The transformer as described above, will be used with an electronic power converter as flyback, resonant or other to transfer a precise power from the primary coil to the secondary circuit. This power will be used by a rotating electronics for measurements and / or pointing a specific direction

The magnetic transformer presented into this paper was designed and optimized using a finite element software. The geometry was designed accordingly to an available volume for a given user context and parametric calculations were defined to get the best geometrical values for the materials that were used and the industrial manufacturing process that will follow the design process. Magnetic calculations were done using a Magneto-static Solver when the ferrite saturation level was analysed and the Eddy Current Solver was used when the inductance values were calculated. The Magneto-static Solver allows taking into account the exact B(H) curve of the ferrite material. The Eddy Current Solver uses a permeability (= μ) function of the frequency and allows to take into account the skin effect into the winding wire. A pre-parameterized adaptive mesh was used. The calculated geometry of the magnetic part is presented in Figure 3.

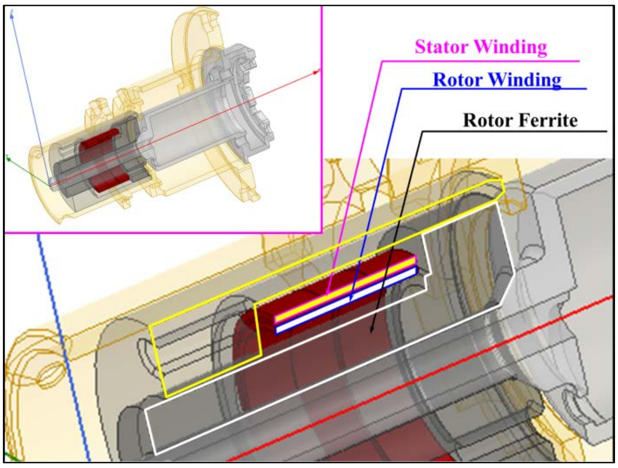


Figure 7: Magnetic part geometry

The two cylindrical gap faces were optimized for a better magnetic flux distribution and a better symmetry of the leakage inductance on both sides of the device

Calculated iso-inductance plots are presented in Figure 4. An objective value of 50μH was aimed. The calculations show finally that a value of 25μH will be reachable considering mean gap between stator and rotor coils, defined by the manufacturing of such elements (in particular ferrites and coils). A good point is that rotor and stator coil inductances are similar and will reach to very good coupling level.

Electric part of the contactless rotary joint.

The electric part of the device is in fact a capacitive transmission line made of two differential channels with a ground ring between. Each channel is made of a pair of conductive concentric rings. The main design is presented in Figure 5. and contain a total of five rings on the stator and five rings on the rotor separated by an airgap. An adequate permeability resin ensures the mechanical position of the rings on the conductive support that make the frame of the device that comprise the connectors.

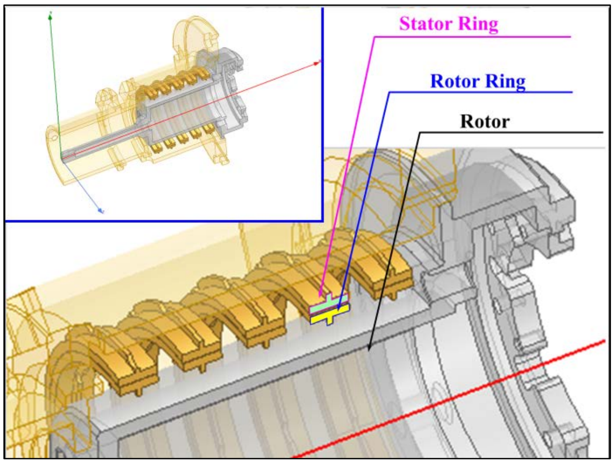
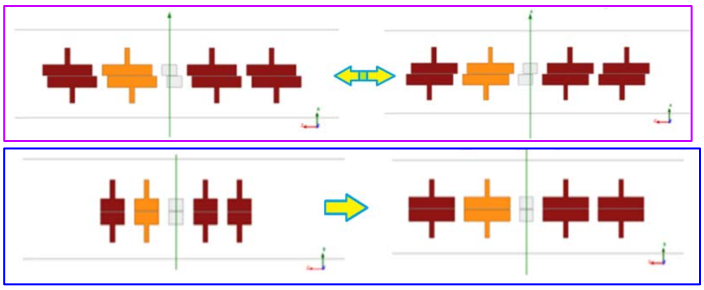


Figure 8: Electric Part design

Parametric calculations were done for different ring heights, different distances between the rings or distances between the rings and the cases. Also, axial miss alignment or different ring shapes was studied Fig.****.



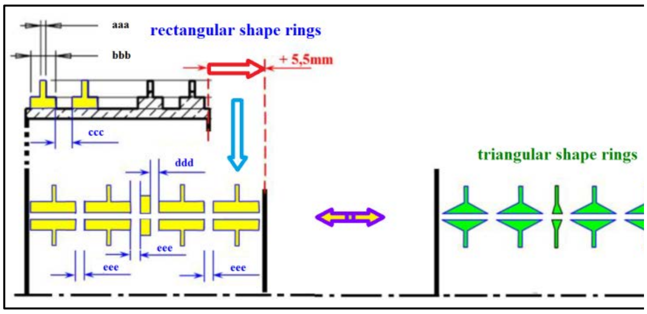


Figure 9 : Example of the different geometrical parameters changes used in calculations

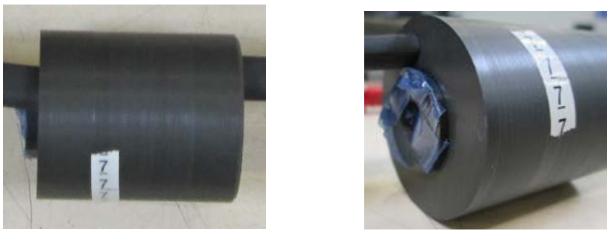
Calculations found that "transmission" capacitance values are around 80 pF. Rotor "crosstalk" capacitance is around 1.18 pF (1.3 pF for stator). Higher capacitance value for the stator can be explained by a larger diameter of the stator rings. Capacitance values between the middle ring and the neighbour rings have similar values to the "crosstalk" capacitance. The "bandwidth" capacitance is around 4 to 6 pF for the rotor and around 5 pF for the stator. Exterior rings present a higher capacitance value because here the capacitances were not balanced yet to get the same value.

INDUCTIVE MODULE'S TESTS

A critical point of the project was to demonstrate the feasibility of machining ferrites with very tight tolerance and to perform a winding with good quality. In deed:

- The ferrite parts were brittle and hard to machine.
- The winding was a complex process to master in this configuration.

A mock-up of the inductive module has been successfully completed after few iterations and then tested.



Mock-up of the Inductive Module

The functional air gap was close to the highest value allowed by the ferrites definition. The value of the inductance was 22µH. A little bit lower than expected, but completely acceptable. This mock-up significantly reduced the technical risk.

SPACE QUALIFICATION PLAN

A qualification plan has been drawn up to demonstrate the compatibility of the contactless rotary joint with space environment. The main tests are as follows:

- Random vibration (from 20Hz to 2000Hz) including a top flat value of $1.2g^2/Hz$ between 100 and 400 Hz.
- Mechanical Shock a SRS including typically 1000g at 1000 Hz.
- Vacuum Thermal Cycling
  - o Temperature: operational from -20°C to +700C
  - o non-operational from -40°C to +80°C
  - o Pressure : 10-6 mbar<P< 10-5 mbar

CONCLUSIONS

The Main difficulty of this rotary joint was to find a good compromise between very low air-gaps around the inductive parts to provide a good electrical coupling, while ensuring enough functional gap for rotating pieces. Analyses were carried out to account for all load cases (mechanical, thermal…) and determine the best functional margins.

Those air-gap values were then input into the magnetic and electronic models, which gave the best performance we could expect for each power and signal module. This allowed to validate the design of the capacitive and inductive modules and the go-ahead for manufacturing.

The inductive module still is deemed the most critical design element of the contactless rotary joint. For example, the accurate machining of ferrites and coils parts is challenging. In addition, the actual coupling performances had to be demonstrated early in the project. This is why an engineering model was manufactured. It is currently under testing, and should ensure that the expected performance can be reached.

A qualification model is also already planned. It will be fitted with the inductive and capacitive engineering modules. It will be then coupled with the electronics units to undergo a global performance test plan. Then it will go through a complete qualification sequence. Final results are expected by the end of 2019, and some will be broadcast at the symposium.

REFERENCES

[1] M. Privat and D. Schwander, "Innovative contactless slip ring," Proceedings of the 12th ESMATS Liverpool 2007.

[2] D. Schwander, « Systèmes de transmission de puissance et de signal sans contact pour applications spatiales: analyse des performances électriques », EPF (Bordeaux) 2012.