A LONG-LIFE CONTACTLESS POWER AND DATA TRANSFER MODULE FOR NEXT GENERATION RADIOMETRY DEVICES

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ABSTRACT

This paper describes the BBM lifetest process and results of a Long-Life Contactless Power and Data Transfer (LLCPDT) Breadboard model including mechanical, power transfer, and data transfer test results and analysis. With support of ESA, a consortium led by SEA Ltd. (UK) has been engaged in the development of a non-contacting modular and generic power and data transfer device for use in future Conical Scanning Imaging Microwave Radiometers. This application is challenging since the life requirement is far beyond anything which is achievable with current contacting technologies in vacuum. From the start of this programme it was also realised that the device might need some relatively novel approaches in terms of bearings and bearing system preloading because of the long life, wide specified operational temperature range, and the potential for quite high thermal gradients across the bearings due to the expected losses from the power transfer modules (200W must be transferred per module at 95% efficiency).

A description is given of the life test setup and test procedure. Successes and difficulties experienced during the test are noted with recommendations for improvements for future tests. The use of wireless transponders for measuring the temperatures of continuously rotating parts, and current and voltage transferred to the rotating side is noted.

A comparison is made between the device specification and observed test results. Static results conducted at SEA in pre-assembly form (i.e. without the full mechanical assembly surrounding and supporting it) are presented alongside results from the fully assembled device through the various stages of testing at ESTL.

Testing is presently ongoing and consists of:

- an initial assembled static check in air,
- a rotational full functional and performance test in air,
- a low speed preliminary test in vacuum and thermal survival tests,
- a cyclically repeated highly accelerated sequence (no power or data transfer while at high speed – 900rpm) with periodic functional and performance testing at the low operational speed (36rpm),
- final phase testing prior to completion.

1. Requirements

The main mechanical and electrical requirements identified for the device are as follows:

Power Transfer (modular):

- Power required 200 W
- Input Voltage 50 V +1% -3%
- Output voltage 50 V +3% -10%
- Power Transfer Efficiency >95%

Data Transfer (modular):

- Data Rate 5Mbps full duplex
- Max. BER (Bit Error Rate) <10-9

Mechanical

- Mass:<8kg
- External Diameter: <250mm
- Length: <250mm
- Through Hole: >50mm
- Bearing Torque: <200Nmm
- Operational Temperature: -40°C to 60°C
- Quasistatic Acceleration: 75g

In addition to the mechanical issues there are also many challenges from an electrical and electronics viewpoint. For example efficiency of power transfer must be maximised so as to minimise the consequences of losses to the bearing system and reliability of high data rate transfer must be guaranteed for the device. Our study has also taken a very detailed and fundamental examination of the various principles and multiple topologies which can be employed for power and data transfer and a system view on the implications of the various technologies for the mechanism and its ultimate application flexibility.

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2. Breadboard Model LLCPDT

2.1 Overview

The overall configuration of the Breadboard model is as shown below in Fig. 1 in which the power transformer conditioning electronics are at the upper end of the mechanism, and the data transfer PCB's at the lower end. The prime and redundant rotary transformer elements which are more critical with respect to alignment than the data elements are positioned between the bearings. In this configuration the BAPS structure (actuator not shown) is able to apply a relative axial displacement to the outer rings of the bearings to increase or decrease the preload on demand.

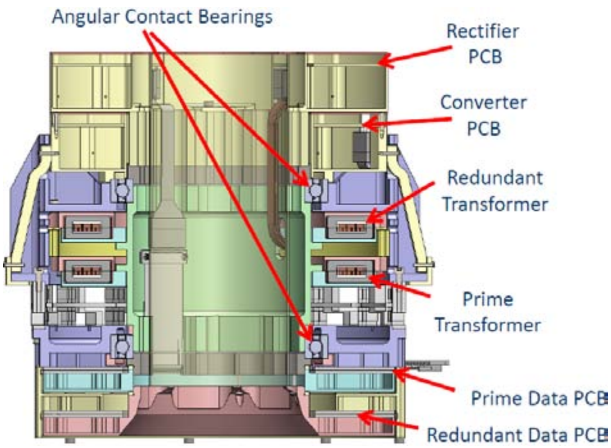

Figure 1. Section View of BBM

One key change from the original baseline design has been the separation of functions such that the PCB carriers do not have to be in place to allow preloading of the bearing assembly to take place. This allowed the assembly process to be simplified and concurrent assembly and tests to take place.

In the Breadboard model it has been necessary to retain the relatively heavy titanium upper bearing housing for stiffness reasons. This coupled with an increase in the mass of the PCB carriers, the total mass of the Breadboard model is 9.4kg (above the original requirement of 8kg). For future models, it is possible that with alternative materials (e.g. albemet), additional light weighting, and if acceptable to the end user, corresponding reduction in bearing housing axial stiffness, then the target mass may still be achievable.

The structure was manufactured predominantly in titanium alloy for mass and stiffness reasons. It was recognised that the poor thermal conductivity of the titanium structure may lead to some elevated temperatures, which resulted in the incorporation of thermal straps.

Fig. 2 below shows a picture of the as built core bearing assembly.

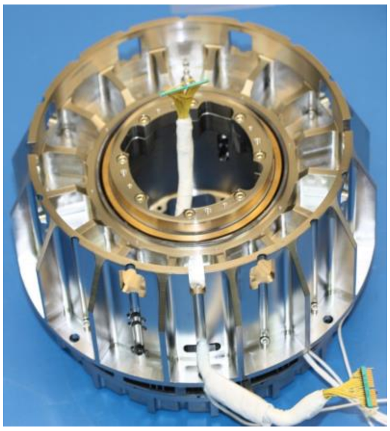

Figure 2. Core Bearing Assembly

The Breadboard model contains debris management features. Voids near the bearing (shown in Fig. 3 below) allow debris to migrate away from the bearing, yet labyrinth seals between rotating and static components minimise further migration towards critical electrical components. In the Breadboard model a single rotary transformer is implemented as shown in Fig. 3 below, with reserved space for a redundant transformer.

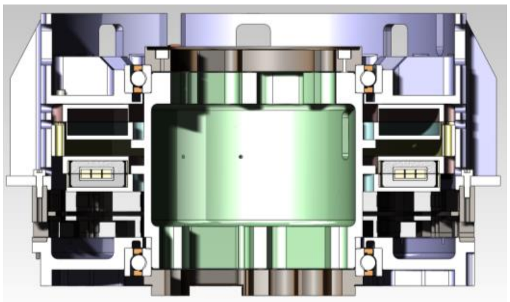

Figure 3. Core Bearing Subassembly CAD cross-section - Debris management voids are visible inboard of the bearings.

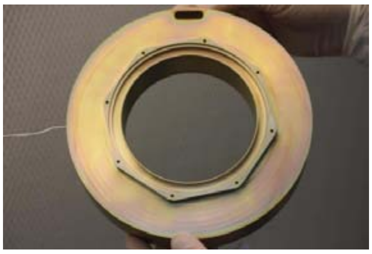

Figure 4. Convertor PCB Enclosure – This component also serves a secondary purpose as the upper-outer bearing clamp, and a tertiary purpose as the upper debris containment void and labyrinth seal.

2.2 Bearing System

The Breadboard Model uses 95mm bore angular contact ball bearings selected primarily for compatibility with the through-hole and loading requirements. These bearings provide very substantial margins in terms of stress and adequate margins against land-over-ride in this application. One downside of this choice was that even given a relatively low effective friction coefficient between balls and raceway, such large bearings require a relatively low and highly compliant preload.

A V-BAPS (Variable Bearing Active Preload System) system in which the preload setting and compliance are totally adjustable was used for the Breadboard model testing. From the point of view of the Breadboard model and its test campaign, the V-BAPS can be considered as test hardware with functionality which uniquely permits:

- Variation of power and signal element spacing on demand by approximately 50µm to examine tolerance effects on performance.
- Variability on demand of local power dissipations to examine sensitivity to thermal loading.
- Variable on demand preload modification to offset (or indeed amplify) the effects of thermal strains.
- Adjustment of bearing preload to confirm as-built torque v preload relationship for the SEA 95 bearings and the susceptibility of the cage stability to preload.
- Low and compliant preload typical of conventional soft preload system.

The achievable preload range in the as-built Breadboard model was determined to be approximately 400N to 1800N. This range is defined by the finite displacement of the BAPS and the real compliances of the interfacing components.

In order to reduce the complexity of the breadboard model thermal vacuum test, the V-BAPS preload was manually adjusted via a rotary feedthrough on the top of the vacuum chamber (rather than an internal drive system).

2.3 Lubricant selection

The lubricant selected for the LLCPDT was PVD (Physical Vapour Deposition) lead applied to raceways and use of a leaded-bronze cage (separator) with alternately slotted ball pockets. This lubricant system has very significant flight heritage in long-life applications and has the advantages of providing a low resistance conductive path for rotor grounding and permitting operation for ground test in air if necessary.

2.4 Thermo-Mechanical Analysis

Thermal analysis showed the transformer and rectifier PCB's would reach an unacceptably high temperature, 119°C, when the upper housing structure was manufactured in titanium. As the only viable method of heat rejection was to conduct heat into the spacecraft mounting interface a change was investigated to the upper housing design to manufacture in an aluminium alloy (accompanied by modifications required in order to maintain the original stiffness). In order to minimise the effects of radial strains on the upper bearing fits, and hence preload, a liner was initially incorporated into the design of the outer raceway/housing interface to reduce the effective CTE mismatch between the bearing steel and the aluminium of the structure itself. When these modifications were made the thermal environment for the PCB's was found to be substantially acceptable, 69°C and the temperature differentials between bearing inner and outer were also within the analysed range (around ±1°C).

While the thermal environment was acceptable, the CTE mismatch between the aluminium alloy housing and the bearing steel was causing high stresses and excessive gapping between bearing and housing at temperature extremes. In addition, the geometrical constraints were such that the baselined stiffness could not be maintained with the material change, resulting in severely decreased preload adjustment range.

After further investigation a compromise of titanium alloy housing with aluminium thermal straps was re-analysed and implemented. These can be seen in Fig. 5 below.

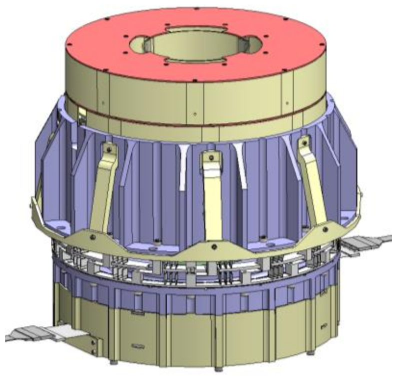

Figure 5. Breadboard Model showing thermal straps

Assembly and preliminary tests are complete, with the life test now in progress.

3. LIFE TEST PROGRAMME

The life test for the Breadboard Model unit will be accelerated by speed alone, with an acceleration factor of approximately 20 being applied such that the test duration is nominally 6 weeks. The life test is split into 3 distinct phases as shown below.

Lifetest Preliminary (low speed) phase

- Functional performance tests over temperature range. Approximately 420,720 cycles at nominal 45 rpm.

Lifetest Accelerated phase

- 4 day cycle
- 8 operational cycles – totalling 30 million revs.
- Each cycle contains full functional and performance test (at 45 rpm).
- Accelerated testing at 900 rpm (power and data transfer off).

Lifetest Final Phase (low speed) phase.

- Functional performance tests over temperature range

Since the test is also required to verify the performance of the power and data transmission elements, the test will be periodically slowed to the nominal operational speed (around 45rpm) in order to verify the validity of the performance of the unit under nominal conditions. One challenge will be to extract the heat from the test system in an appropriate way. It has been concluded that a test in which power is passed across the rotating interface then returned to the static interface would risk over-test and be thermally unrepresentative, therefore the test setup will incorporate a 300mm diameter radiator on the rotating side which will radiate with good view factor at 200°C to the upper heat exchanger in the test chamber such that the expected 200W of power can be dissipated.

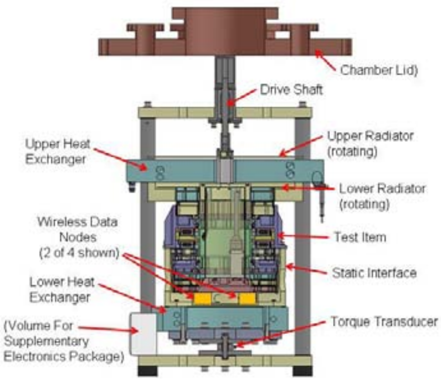

Figure 6. Section View of breadboard model in test rig.

Two heat exchangers are utilised (Light blue). The device is driven externally, while torque is measured internally.

The photograph in Fig. 7 highlights the system complexity required to test the device. On the static side there are a range of sensors to measure multiple temperatures, strains, and torque. In addition to the rotating side power dissipation, three wireless data acquisition and transmission nodes are included, attached to the bottom of the rotating components of the device, which enable telemetry to be wirelessly transmitted out of the vacuum chamber while under test at a wide range of temperatures. These devices provide data on internal temperatures of the rotating components which is essential to ensure the upper radiator disc does not overheat.

Figure 7. Assembled life test rig with MLI and Thermal Vacuum chamber lid. Upper radiator disc is visible with heat dissipating resistors.

3.1 Wireless Nodes

The Breadboard model life test utilises SEA developed wireless transponders for measuring the temperatures of continuously rotating parts, and current and voltage transferred to the rotating side. The wireless sensors were originally developed under the ESA Low Power Proximity Network of Sensor study and have been developed further as part of this development.

The wireless nodes are battery powered with configurable sleep times to extend battery life. Two wireless nodes are used for measuring temperatures on the rotating side, with a third used for measuring current and voltage (power transfer calculation).

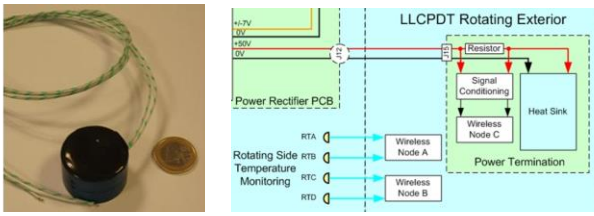

Figure 8. Wireless Nodes.

4. LLCPDT Test Campaign

4.1 Power Transfer Testing

The power transfer is achieved by the use of a rotary transformer with converter and rectifier modules. The modules are shown in Fig. 9 below.

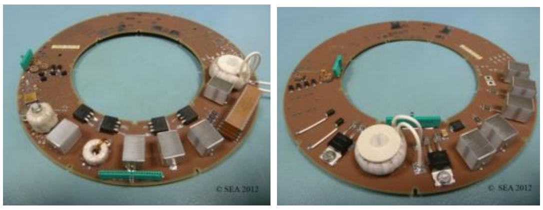

Figure 9. Power Converter and Rectifier Modules.

Once assembled the modules were subjected to extensive Integrated Converter / Transformer / Rectifier static tests were conducted at SEA prior to assembly into the Breadboard model. End to end efficiency and regulation tested under variation of these variables independently:

- Air Gap 0.1-0.5mm in steps of 0.1mm
- Frequency 70-130Khz in steps of 5kHz
- Load 1W – 210W – 9 steps
- Tilt ±0.01°
- Line voltage 48.5V, 50V, 50.5V

These tests demonstrated that the system was resilient to minor variations in design variables. Fig. 10 below shows the effect on efficiency vs load curve of varying transformer air gaps. The efficiency is above 95% for output load power from 120W to over 200W at rated 50V input voltage.

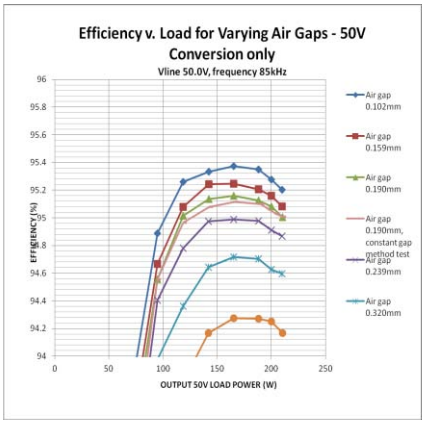

Figure 10. Module testing : efficiency vs output power

Once system testing was successfully completed, the power transfer elements were then incorporated within the Breadboard model. Once installed, only the line volatage can be varied. The nominal transformer air gap is nominally 190µm within the assembled Breadboard model.

Fig. 11 below shows the nominal transformer primary mounted within the Breadboard model.

Figure 11. Rotary Transformer primary mounted

During operational portions of the life test (nominal rotation speed) 200W power is transferred across the Breadboard model to a resistive load. The voltage and current are measured on the input (static) side by a wireless node external to the vacuum chamber. The voltage and current are measured at the resistive load by a wireless node internal to the vacuum chamber. The comparison of instantaneous voltage and current allows power transfer efficiency to be compared.

Fig. 12 below illustrates efficiency tests in vacuum at 20°C for varying input voltages and rotation rates. The efficiency varies up to a maximum of 93.75%. The efficiency is below 95% as the data transfer module is being powered internally to the Breadboard model (this power draw cannot be separated out). The data transfer circuits use more power when running at 5MHz than at idle (greater than 94% efficiency achieved with the data transfer circuits at idle).

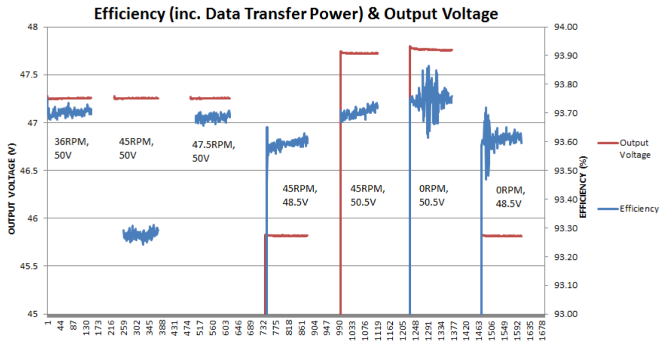

Figure 12. Output Voltage & Efficiency at different input voltage levels /rotational speed

Efficiency climbs when the converter is turned on from cold (this can be seen in Fig. 12), this is a thermal effect. In all cases the efficiency remains above 93% (including the data transfer power usage). The output voltage has been observed to be within specification at the different input voltages (48.5V, 50V & 50.5V). In summary power transfer is performing in accordance with expectations.

4.2 Data Transfer Testing

The data transfer is achieved by the use of capacitive coupling. The design was for a two plate pair (nominal and redundant). One of the modules is shown from above in Fig. 13 below.

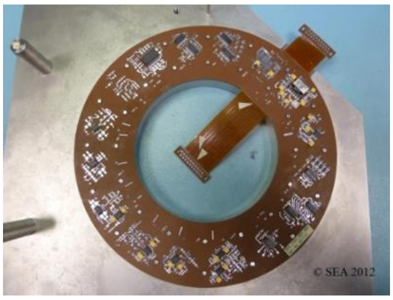

Figure 13. Data Transfer Module

A Bit Error Rate Tester (BERT) was used to verify that the BER of the LLCPDT Breadboard model was $<10^{-9}$. The BERT is a test pattern generator which uses predetermined stress patterns consisting of a sequence of logical ones and zeros generated by a test pattern generator. Data is sent through the Breadboard model and looped back on the rotating side. The BERT counts the number of errors between transmission and reception. The requirement requires less than 1 in 1,000,000,000 bit error failures.

Once assembled the modules were subjected to extensive uplink and downlink BER & Signal Integrity static tests conducted at SEA prior to assembly. Critical parameters were varied whilst monitoring the BER for signs of degraded performance. Table 1 below shows the results of this testing.

Table 1. Data Transfer Module testing

Variable	Tested Range	Operating Range	Conditions
PCB Separation	0.3mm to 2.9mm	0.3mm to 2.1mm	5MBits/s, 0mm misalignment, 0° tilt
PCB Misalignment	0mm to 2.9mm	0mm to 2.9mm	5MBits/s, 0.5mm separation, 0° tilt
PCB Tilt	0° to 0.21°	0° to 0.21°	5MBits/s, 0.5mm separation, 0mm misalignment
Data Rate	1Kbits/s to 12MBits/s	1Kbits/s to 8MBits/s	0.5mm separation, 0mm misalignment, 0° tilt

As can be seen by Tab. 1 these tests demonstrated that the data transfer was resilient to minor variations in design variables.

Once module testing was completed, the data transfer elements were then incorporated within the Breadboard model. Initial integration testing failed due to zero data transfer. The issue was traced to data transfer components clashing with PCB carriers causing a short circuit which prevented correct transfer of data. Onec this clash was resolved the data transfer worked correctly with no issues.

The testing during life test measures the combined uplink and downlink signal integrity and BER under the conditions of:

- ≈1 Hour at High Preload
- ≈1 Hour at Intermediate Preload
- ≈1 Day at Nominal Low Preload
- ≈1 Hour at Virtually Zero Preload

In the operational life test so far no data transfer bit errors have been reported by the BERT equipment. Nominal rotational speed has also increased from 36rpm to 45rpm with no impact on BER observed. From data transfer testing carried out so far, SEA believe the Breadboard model could achieve a data rate of 8MBits/s and with a known PCB change could achieve in excess of 10MBits/s.

4.3 Mechanical Testing

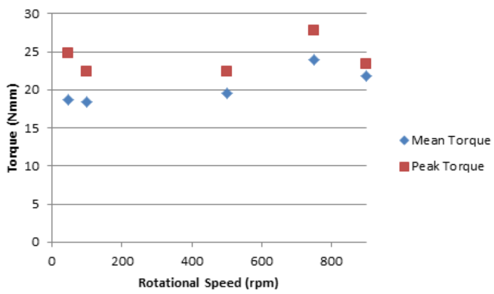

Figure 14. Torque Vs Rotation Speed – In vacuum. Preload of 860N

A preliminary "High-Speed Check-out" was conducted prior to the lifetest to confirm the desired accelerated test speed is achievable. The device and test rig survived all rotational speeds up to and including the maximum test speed of 900rpm. It was noted that at around 700rpm, the test rig passed through a minor resonance, and hence this may have had some effect on increasing the torque recorded at 750rpm. Otherwise, the torque level is as expected for this device, and retains the solid lubrication characteristic of torque independent of rotational speed.

Bearing reversals at the nominal speed of 45rpm have been performed at 20°C and 60°C in vacuum. The results of which are presented above. The BAPS arrangement permits successful preload adjustment while the unit is under test through a range of approximately 400N to 1800N. The requirement for a maximum on-orbit torque of 200Nmm looks realistic, as the initial mean torque at 20°C is a factor of 20 below that requirement.

The 20Nmm increase in torque measured at 60°C relative to 20°C is of the expected magnitude as the thermal gradient recorded was with the outer race 2°C cooler. Therefore, these preliminary results indicate that the torque thermal sensitivity at start of life is not abnormal.

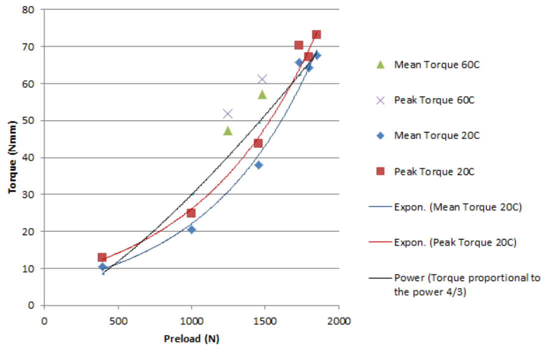

Figure 15. Torque Vs Preload – In vacuum. Exponential trendlines added for 20°C data

5. CONCLUDING REMARKS

Breadboard model tests of key elements of the design at both the module level and from the assembled model life test results achieved to date show good agreement with predictions and demonstrate that the system can fulfil its power and data requirements when used.

The key power and data transfer elements of the design are entirely modular and expandable. The BBM testing demonstrates the performance of the system with a BAPS-enabled bearing system and will also provide data on the sensitivity of the design to bearing dissipations at different temperatures in order to validate the modelling of the device and minimise the development risks for future models.

The full breadboard system is currently in lifetest, with full results to presented at the next possible opportunity.

6. ACKNOWLEDGEMENTS

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