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

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ABSTRACT

This paper describes the preliminary development phases of a Long-Life Contactless Power and Data Transfer device (LLCPDT) including the evolution of the topology of the device, the main drivers in selection of bearings, the preloading system and the lubrication. The design of the system proposed and the preliminary characterisation at breadboard level of its key elements are presented.

1. INTRODUCTION

Conical Scanning Imaging Microwave Radiometers have been making a significant contribution to operational meteorology and climatology since the first launches with Seasat and Nimbus 7 in 1977, then more recently with the DMSP series of satellites (SSM-I and SSM-IS), TRMM, EOS-Aqua and Windsat [1,2,3].

Within Europe, attention is now strongly focused on the development of the payload complement for the Second Generation MetOp programme which includes two conically scanning microwave instruments, the Microwave Imager (MWI) and the Ice Cloud Imager (ICI).

The primary objective of the MWI/ICI instruments is to support Numerical Weather Prediction at regional and global scales, through the provision of:

- Cloud and precipitation products including bulk microphysical parameters
- Water vapour and temperature gross profiles
- All weather surface imagery including:
  - Sea surface temperature (SST) and ocean salinity
  - Sea ice coverage (and type)
  - Snow coverage, depth and water equivalent
  - Soil moisture products
- Sea surface winds (complementary to the scatterometer)

As well as providing continuity of other earlier microwave imager channels in support of long-term climate records.

Both of these instruments employ a conical scan pattern which is achieved by rotating the main instruments reflector and body, including all of its active receivers and electronics. This configuration requires some means of transferring, power to the instrument rotor, as well as transferring bi-directional signals across the rotating interface. A typical instrument configuration is shown below in Fig. 1.

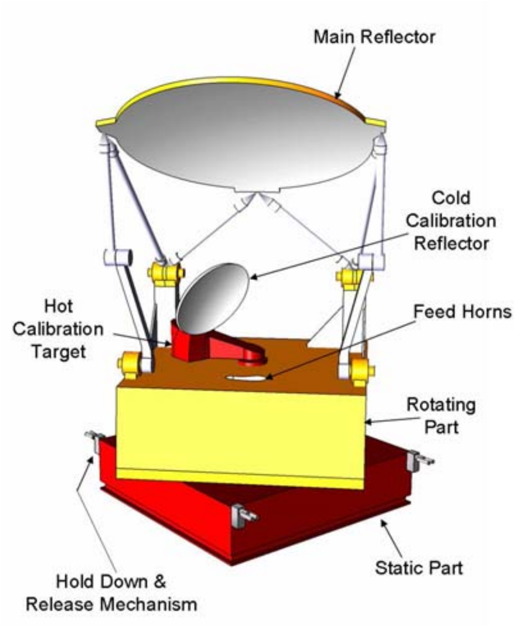

Figure 1. Typical Radiometer instrument Configuration

From the above it should be noted that while the main instrument assembly is rotating there are hot and cold calibration targets that are static and these are supported by a central static structure. This implies that the scanning equipments including the power and signal transfer devices must provide a substantial

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through hole to accommodate this central static structure. This is an important constraint that significantly influences the design of the mechanism elements as it limits the access to the rotation centre. It also imposes limitations on the minimum size of scanning components including the size of bearings and the diameters (hence sliding rolling distances) of any contacting power/signal transfer devices, such as slip rings. This aspect is extremely critical as this new generation of instruments require high operating reliability over an on-orbit life time of 8.5years. In addition the expected scan patterns are based on constant speed rotation at a rate of up to 38revs/min. This gives a required life of up to 170million revolutions (without margins or ground testing). In terms of equivalent sliding distances this equates to approximately 40000km.

Even with optimised materials and contact geometry this magnitude of sliding distance for any contacting device inevitably means the generation of substantial amounts of conductive wear debris which constitutes a major risk to reliable repeatable operation over a long period of time. Even with specific measures to "manage" this debris the inability to representatively generate the sustained zero-g condition means that actual debris deposition cannot be predicted or controlled and so the validity of accelerated life testing on ground is highly questionable.

Given this, the expected high number of channels, and the need for high (and predictable) reliability, there are serious concerns that current contacting power and signal transfer technology would not adequately meet the needs of the Second Generation Metop instruments.

Therefore, 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. This application is challenging since the life requirement is way 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).

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.

In recent years various approaches to the problem of power and data transfer have been examined and some described in past ESMATS or other open literature papers [4,5,6,7]. However the technology which is the subject of this paper is novel because from the start of it's development the flexibility of the device to accommodate wide ranging instrument requirements which lead to different bearing systems, at one extreme using a conventional compliant bearing preload system, through a fully variable device and also a dedicated bearing offload device, has been a priority.

2. DEVICE REQUIREMENTS AND CANDIDATE TECHNOLOGIES

We review below the outline requirements and list candidate technologies for the trade-offs.

2.1. Overview of main mechanical and electrical 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 order to be flexible concerning the configurations which can be supported, the device is also required to be capable of operating with either inner or outer rotating and therefore of transmitting power and data both to or from the rotor (whether shaft or housing).

2.2. Power transfer requirements & potential technologies

There are a number of key performance requirements that are specific to the design of the contactless power transfer module for example:

- Each power transfer channel (main and redundant) must individually be able to transfer 200W from the stator to the rotor and vice versa.
- Power transfer must be compatible with a spacecraft bus voltage range 28-50V, with the latter being the optimised reference voltage at which the efficiency requirement is to be met.
- The electrical efficiency of the complete transfer system must exceed 95% under full power transfer conditions at the optimised reference voltage (+1%/-3%). This is particularly challenging as is includes the AC/DC/AC power conversions as well as the losses in the transformer.
- The output voltage must be 50V (+3%/-10%).
- The voltage stability must be $\leq$ +/-3%

A key feature of the device is that it must be capable of meeting the specification throughout its intended lifetime within the intended environment.

Furthermore it was requested that the design of the power transfer components should be modular thereby allowing ease of potential future expansion to larger power requirements or modification to match different needs.

The main requirement of transferring 200 Watts at greater than 95% efficiency is a significant filter for the selection of power transfer techniques. Very few contactless techniques can achieve this 95% efficiency requirement and therefore the list of suitable candidate technologies for the LLCPDT was small. The following power transfer options were initially considered although most were found to be very unlikely to pass the efficiency criteria at the required power levels:

- Transformer-based
- Microwave-based
- Optical-based
- Generator-based

2.3. Data transfer requirements & potential technologies

As for the power transfer function there are a number of key performance requirements that are specific to the design of the contactless data transfer module and these are listed below. The unit must:

- Transmit digital serial data from the rotor to the stator and vice-versa at a rate of 5 Mbit/sec and in full duplex mode.
- Have a bit error rate (BER) of less than 10^{-9}
- Provide full functionality with either main or redundant channels

Again, in a manner similar to the power transfer module, it is essential that the data transfer components are of a modular design for the same reasons of potential future expansion or modification to match different needs whilst maintaining it's performance requirements throughout the intended lifetime within the intended environment.

The following techniques have been identified as the main contactless data transmission techniques potentially applicable to this application:

- Capacitive coupling
- Transformer coupling
- Radio Frequency (RF) transmission
- Optical transmission

2.4. Mechanical requirements & potential technologies

In addition to the above outline specification values, from our knowledge of the application some further self-imposed, but nevertheless important mechanical architecture requirements were derived which include:

- The device should have a capability for a large through-hole up to >70mm diameter.

- The device should have a capability either to support the rotating payload mass of the radiometer system (in the case of a smaller payload unit) with compatible launch frequency and vibration levels or to be off-loaded in the case that the system mass requires an auxiliary bearing or offload system for launch. In this case the rotor should be capable of axial translation in a defined direction by up to 500μm for the purposes of axial offload and launch protection.

  Given this, that the gap between the power transfer elements is relatively small and that the potential position sensing elements at system level may also require small axial clearances and suitable protection, it is clear that both under launch vibration and under the influence of an external axial offload system, the LLCPDT should be capable of very limited axial translation in one sense, but relatively large axial translation in the opposite sense IF required.

- Due consideration to be given to the accommodation of cables for power and signal and their efficient and hazard-free routing within the mechanism during assembly.

- The requirement for the system to be electrically grounded through the bearings (rather than via separate dedicated grounding measures) was ultimately significant in the lubricant selection (as discussed later)

3. TRADE-OFFS

The three principal elements of the LLCPDT, namely Power and Data Transfer Modules and the Bearing/Lubrication configuration, were subjected to systematic trade-offs.

In order to perform the trade-off efficiently and transparently, and to deliver an optimal design the trade-offs were conducted as a two-stage process.

Firstly from a review of the requirement specification a short list of "killer criteria" was established to provide a means of focusing on the feasibility of each option and thereby filtering out any non-credible solutions. Advantages and disadvantages for all candidate concepts were summarised and non-credible or marginal options were eliminated by applying the "killer criteria."

Secondly, using agreed selection criteria the short list of design options was evaluated for suitability with the selection criteria ranked by paired comparison to establish weighting factors. A trade-off summary table was then generated based on both weighted and un-weighted criteria which allowed the visibility of clear winners.

3.1. Discussion of electrical trade-offs & solution adopted

Power Transfer

For power transfer the "killer criteria" identified and applied were:

- Efficiency >80% (PT1)
- Life-time potential >7 years (PT2)

From this the following selections were traded-off

No.	Option	PT1 (>80% efficiency)	PT2 (>7 year life)
1	Rotary transformer (10-200kHz)	Yes	Yes
2	Facing PCB microstrip antennas (1-10GHz)	No	Yes
3	Spiral rotary waveguide (2.45-24GHz)	No	No
4	Solar light source to triple-junction cell	No	No
5	Laser diode array to GaAs cells (808nm)	No	No
6	Dynamo with stator coils (23x23cm)	No	Yes

Table 1. Application of Power Transfer Killer Criteria

It was judged that the rotary transformer had potential to have an efficiency of >95%, and, if well engineered should not have any significant performance degradation over life. Microstrip Antennas suffer from low efficiency <32% due to the central through hole and near field effects. The Rotary Waveguide offers 59% efficiency but short expected lifetime due to high power dissipation. The Solar Light and Laser Diode solutions were also judged to be low efficiency and would be very susceptible to degradation from contamination and damage from and radiation effects. The Dynamo was judged not mass or volume efficient and would require high speed operation to offer electrical power transfer, its efficiency would be <70%. The rotary transformer was the only option passing the killer criteria and was therefore selected.

There are two basic configurations shown in Fig 2 and Fig. 3 options which were considered further.

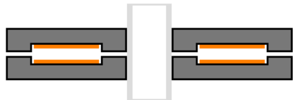

Figure 2. Opposing Discs

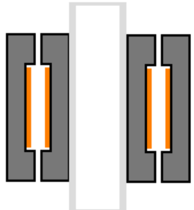

Figure 3. Concentric Cylinders

To provide redundancy both prime and redundant transformers need to be incorporated into the design. A number of different configurations were considered as shown below.

Figure 4. Concentric Cylinder Options (a)- left and (b)- right

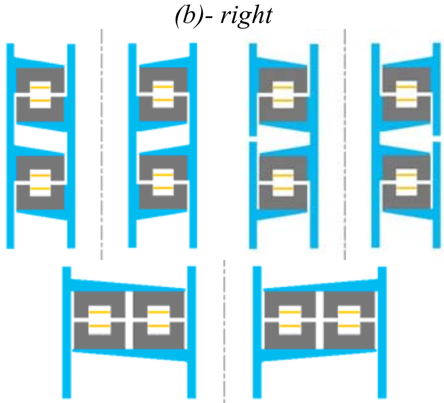

Figure 5. Opposing Disc Options (a) – left , (b)-right and (c)- lower

Both concentric and opposing disc configuration types were subjected to 2-D magnetic modelling (e.g. Fig. 6) and were found to have comparable performance. Thus the ultimate selection of the design centred around the ease of manufacture and assembly, the number of different component types required and the ease with which the 200μm transformer gap could be achieved and maintained. The concentric cylinder design allows relatively easy control of this gap whilst being tolerant to some axial tolerance build-up. This is in sharp contrast to the difficulty of manufacturing the ferrite ring assembly and installing the windings in place. On the other hand the opposing disc scheme needs careful control of manufacturing tolerances but requires only one part type to be manufactured. Assembly is straightforward and the windings can be manufactured separately and then installed into the ferrite transformer rotor or stator.

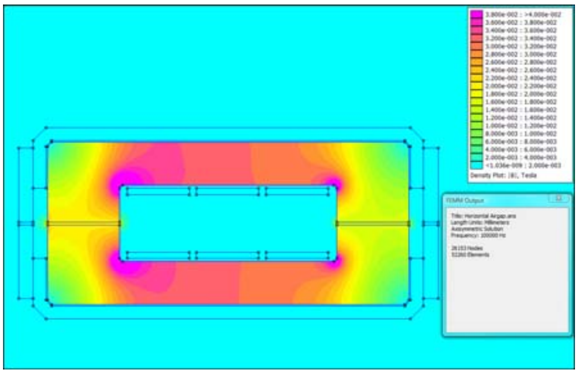

Figure 6. Flux Density Distribution B-Field Inside the Transformer Ferrites

Data Transfer

The data transfer killer criteria identified and applied were:

- Data transfer rate>5Mbps with BER<10^{-9} (DT1)
- Life-time>7 years (DT2)

No.	Option	DT1 (>5Mbps & <1x10^{-9}BER)	DT2 (>7 year life)
1	Capacitive coupling	Yes	Yes
2	Inductive coupling	Yes	Yes
3	Radio Frequency (WiFi)	Yes	Yes
4	Axial optical waveguide channel	Yes	No

Table 2. Data Transfer Killer Criteria

As with the power transfer the susceptibility of the optical option to contamination and radiation damage eliminated it from further consideration.

The three remaining options were then put through a more detailed selection process based on the selected criteria of: life/reliability, performance/features, upgrade-ability, recurring costs, interfaces/properties and design and development risk. Being an unproven technology for space use the RF option represented a design and development risk, it also represents a significant EMC interface risk with other spacecraft equipment.

The winner of the formal trade-off was the Capacitive Coupled option, however this could be configured in various geometries as shown in Figs.7 to 9 below.

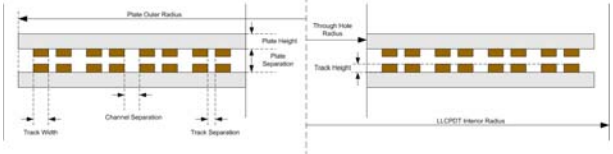

Figure 7. Single Plate-Pair with prime and redundant

The single plate pair is the most volume efficient but requires the majority of the allowable diameter to be used.

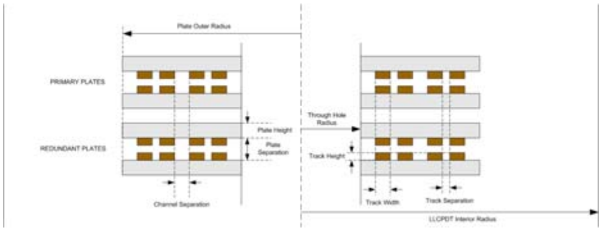

Figure 8. Two Plate-Pairs, prime and redundant

The two plate-pair geometry is similar to the single plate-pair but now has the advantage that the primary and redundant channels have contamination and wear failure modes that are independent of each other, reducing the risk of total data transfer system failure

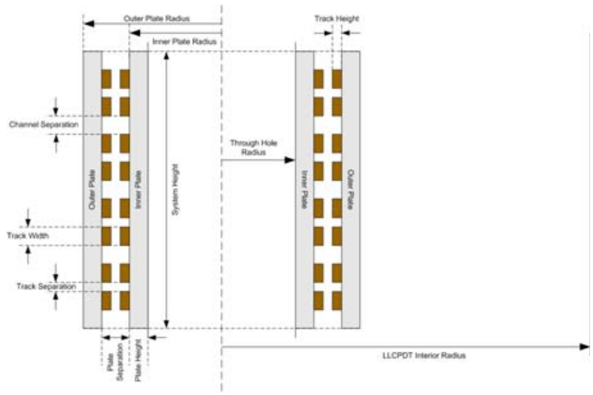

Figure 9: Single Plate Pair Mounted Axially with Flat Tracks

The axially mounted single plate pair option has the potential to allow close control of the capacitive gap as the radial tolerances are more likely to be easily controlled than axial tolerances that will affect the performance of the flat plate-pairs. It also readily allows axial movement in either direction for any bearing off-load system. Its performance is predicted to be similar to the first two options but would represent a challenge to be manufactured using traditional PCB techniques.

One of the main mechanical considerations with the capacitively coupled design is the achievability of sufficiently flat and parallel tracks. The capacitively coupled solution is easily realised through the use of PCBs, which however, are manufactured to a relatively poor flatness tolerance when compared to tolerances achievable with machined metallic parts.

Given the above it was concluded that the Two Plate-Pairs provided the best overall option especially if variations in flatness are minimised on assembly to suitable support structures.

4. ELECTRICAL BREADBOARDING

Electrical breadboard has begun at SEA and is still in progress at the time of writing. Results will be presented at the conference.

The power transformer breadboard prototype is a topological equivalent being realised with COTS ‘E’ cores.

Figure 10. Prototype Transformer showing Litz Wire windings

Similarly the capacitive data transfer design has been prototyped using COTS components.

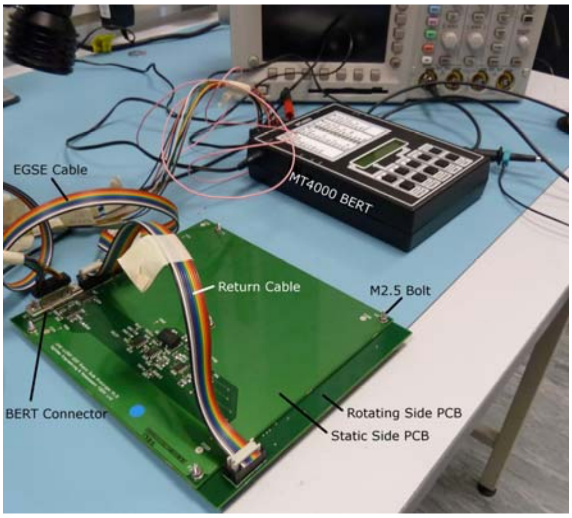

Figure 11. Prototype Data Transfer PCBs in a BER test

5. MECHANICAL DESIGN DETAILS

5.1. Bearing system

The baselined design 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.

In the early stages of the design one identified 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 in order to have potential to meet the demanding on-orbit torque requirement over the wide operational temperature range. Furthermore since large thermal differentials were initially expected between inner and outer rings this would likely drive the choice of a compliant preload system.

Various preload configurations (duplex, hard preload, back-back spaced, hard and soft preload etc) were considered, at the trade-off stage, however for maximal angular stiffness during launch, an axially spaced bearing configuration was adopted. For minimal sensitivity to thermal strains this system required a high preload compliancy (i.e. low stiffness) on-orbit.

Due to our involvement in other studies and flight activities it was identified that a technically optimal solution might include the use of a Bearing Active Preload System (BAPS) [8,9,10] which could give a very high preload and preload stiffness for launch, but highly compliant and low preload on orbit. A variant of this system in which the preload setting and compliance are totally adjustable (known as “V-BAPS”) was baselined for the breadboard model since it could provide a high and relatively rigid preload of order 2500N for launch, thus preventing gross axial gapping of the bearings yet low and relatively compliant preload on-orbit (200-300N and ~ 5-20N/µm) with commensurately low peak Hertzian ball-raceway contact stress ~600-700MPa for nominal on-orbit conditions.

The V-BAPS also provides the potential to modify the preload of the unit once built to accommodate effects of thermal strains and to permit the sensitivity of the design to dissipations in the bearings to be explored experimentally during the development.

In-line with the flexibly configurable system philosophy identified in Section 1 above, it should be noted that whilst providing some significant benefits in this application for reasons of ultimate flexibility the BAPS is not necessarily and integral part of any finally developed flight design derived from this breadboard programme. Where appropriate the BAPS could be replaced by a fixed but compliantly equivalent low preload system (in the case that its use might not be justified) provided suitable provision is made to prevent bearing degradation resulting from the gross axial gapping under launch vibration or if a separate bearing offload system is used. The LLCPDT design is sufficiently flexible to permit optimisation of the preload system to the specific application.

5.2. Lubricant selection

A formal trade-off was carried out from which 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 [11,12,13] 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. As with all solid lubricants , one disadvantage of this lubricant type in long-life applications is the need to manage debris generated, however it has been shown [14] that the wear rate is approximately linearly proportional to preload and hence operation at a relatively low preload (equivalent in stress terms to operation around 25-50N for the EX25 bearings in Fig 12 below) as in the case of LLCPDT offers the best potential to minimise debris generation and maximise ultimate bearing life.

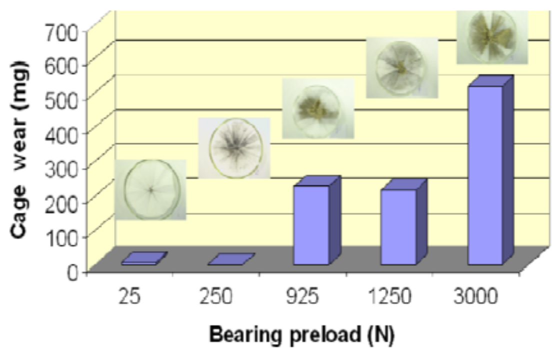

Figure 12. Cage wear (mass basis) v bearing preload for 10 million rev. test using EX25 bearings with leaded-bronze cage as a function of preload ([14], images show wear debris rinsed from bearings)

Typical predicted peak torque for the LLCPDT bearing system as a function or outer and inner ring temperatures is shown in Fig. 13 below. For thermal gradients of ±10°C the performance is within the 200Nmm budget, however for larger gradients the trend suggests that the torque budget would not be met or the preload would be reduced to zero. However by adjustment of the BAPS the overall preload level can be reduced or increased to offset the thermal effects and maintain the bearing performance within specification for a much wider temperature range or for a much wider thermal gradient if required.

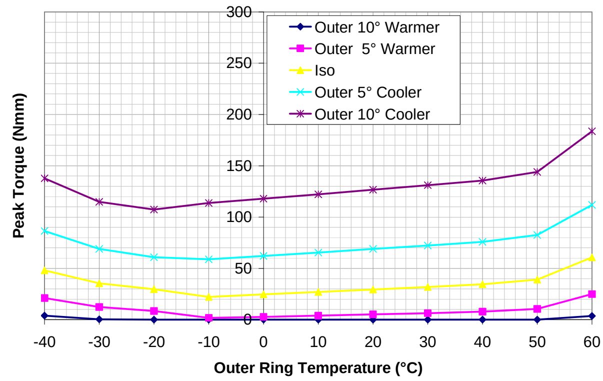

Figure 13. Predicted Peak Bearing Torque v Outer Ring Temperature and Inner/Outer Differential

5.3. Baseline Mechanical Configuration

The first iteration baseline configuration is as shown below, Fig.14 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 which will increase or decrease the preload on demand. If a conventional housing were used, then a compliant element (e.g. Bellville spring or diaphragm would be required).

The structure in the first iteration configuration was manufactured predominantly in titanium alloy for mass and stiffness reasons and whilst it was recognised that the poor thermal conductivity of the titanium structure might lead to some elevated temperatures, this structure was baslined for the thermal analysis.

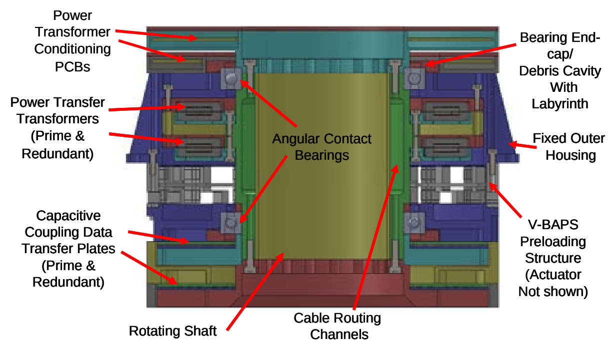

Figure 14. Section View of Initial Baseline Mechanical Configuration

5.4. Thermo-Mechanical Analysis

Initial thermal analysis showed the transformer and rectifier PCB's to reach unacceptably high temperatures, 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 made to the upper housing design to manufacture in an aluminium alloy (accompanied by modifications required in order to match the original stiffness). In order to minimise the effects of radial strains on the upper bearing fits and hence preload a liner was 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) as shown below .

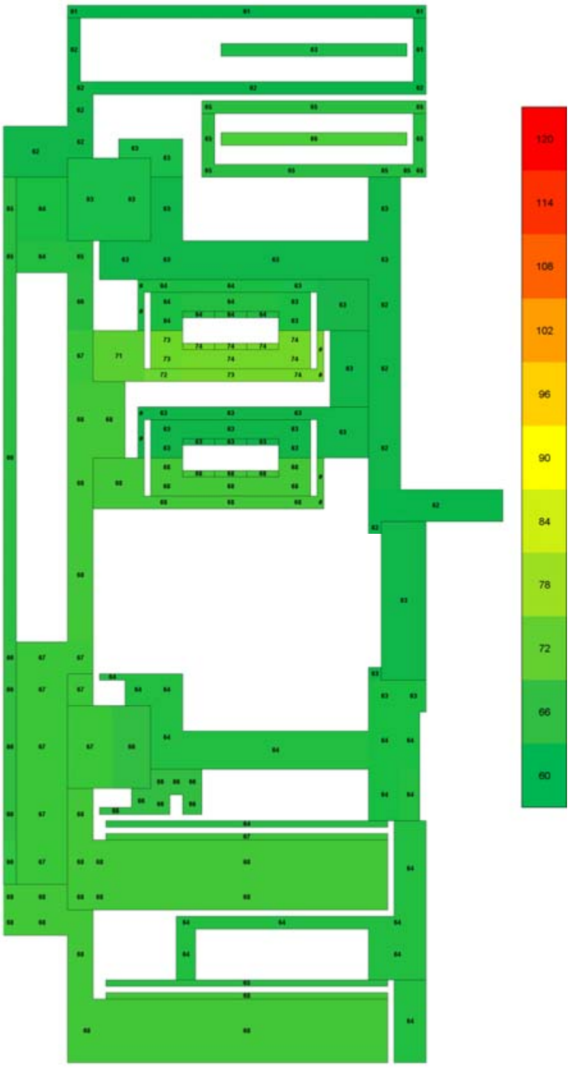

Figure 15. Temperature Profile (Half Section View)

On the basis of this analysis the design of the unit was finalised and manufacture has begun with the intention of commencing the lifetest in the coming months.

6. LIFETEST PROGRAMME

The lifetest for the Breadboard Model unit will be accelerated by speed alone, with an acceleration factor of approximately 15 being applied such that the test duration is nominally 6 months .

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 36rpm) 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 100°C to an internal shroud in the test chamber such that the expected 200W of power can be dissipated.

7. CONCLUDING REMARKS

A baseline design of a system which on the basis of analysis is capable of meeting the requirements has been developed. So far, breadboard-level tests of key elements of the design show good agreement with predictions and demonstrate that the system is likely to fulfil its power and data requirements.

The key power and data transfer elements of the design are entirely modular and expandable and the planned BBM testing will not only demonstrate the potential performance of the system if used with BAPS-enabled bearing system, but 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 which may have different bearing preloading systems commensurate with the optimisation of the bearing system for the specific application.

The full breadboard system will be manufactured in autumn 2011 and tested in early 2012.

8. ACKNOWLEDGEMENTS

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