ANTENNA DESPIN MECHANISM FOR BEPI COLOMBO

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ABSTRACT

The Antenna Despin Equipment for the Mercury Magnetospheric Orbiter (MMO) of Bepi Colombo contributed by JAXA consists of two major elements. One is the Antenna Despin Mechanism (ADM) dedicated to rotate the High Gain Antenna (HGA) at the spin rate of the S/C, the second important element is the Antenna Despin Mechanism Control Electronics (ADMCE) used to command and control the ADM.

Given by the nature of the application, a highly constant rotational velocity is a key requirement. Therefore not only the mechanism design itself plays an important role, but also the Control Loop included into the ADMCE FPGA is of key importance to achieve the performance under the given environmental conditions.

1. INTRODUCTION

The MMO S/C will be launched when mounted on top of the European Mercury Planetary Orbiter (MPO). After completion of the cruise phase to Mercury, the MMO will be separated from the MPO and both S/C will operate independently.

The MMO S/C is dedicated to a magnetic science mission in an elliptical Mercury orbit. Astrium GmbH Satellites has developed and qualified the ADM equipment under NEC contract. The PFM dedicated to the FM Satellite is presently under integration and will be delivered to the customer in spring 2010.

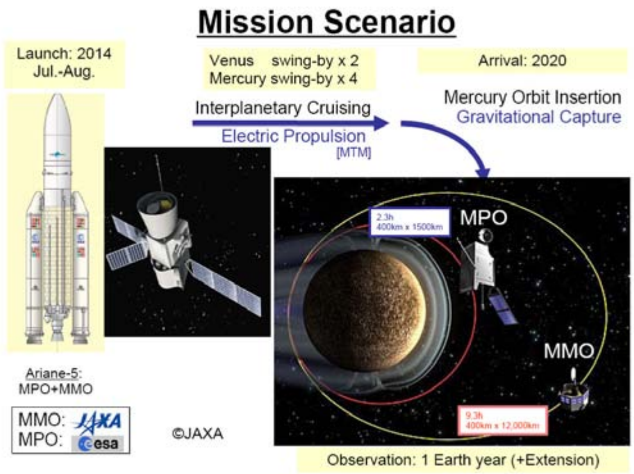

Fig.: 1 MMO Mission Scenario

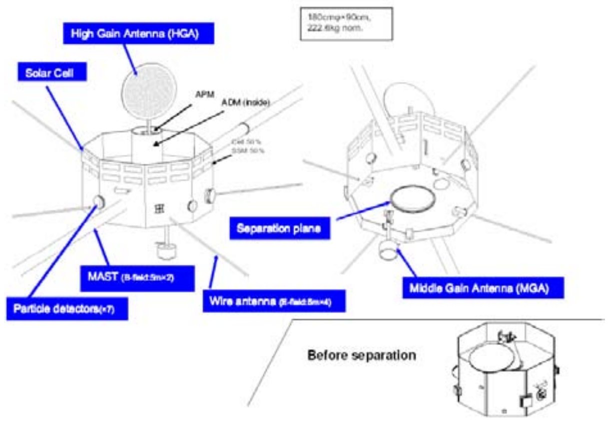

Fig.: 2 MMO S/C with HGA and ADM mounted on Top

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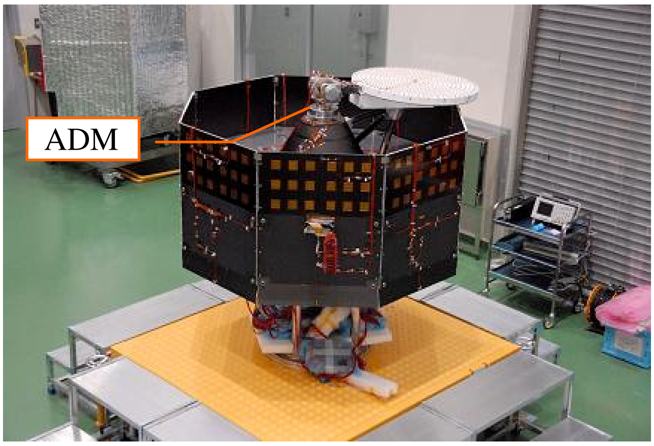


Fig. 3 MMO(M T M) and ADM mounting position
MTM:Mechanical Test Model Courtesy of JAXA

2. ADM OVERVIEW

The ADM design was worked out with the goal to reduce as much as possible the mechanism complexity, so to cope with the elevated temperature range, the temperature variations over orbit, the stringent requirements for position drift per time increment and the life and reliability requirements.

An extensive thermal analysis was started at the beginning of the design phase in order to identify the potential for temperature reduction in the ADM mounting compartment thus to allow the ADM to operate in a moderate thermal environment. The critical element in this respect was the thermal limitation defined by the optical encoder. Therefore effort was spent to realize an ADM design which maintains the encoder temperatures within acceptable limits.

The ADM includes a bearing unit to take over the launch loads and to support the HGA S/S, a fully redundant brushless DC motor with two independent stators for reliable motion, a high resolution optical encoder for position feedback, a slipring unit for power and signal transfer to the HGA S/S and a X-Band Rotary Joint for RF power transfer.

The slipring is designed in hollow shaft configuration in order to allow the accommodation of the bearing-less Rotary Joint.

The design was optimised for thermal match over a wide thermal range and for maximum compatibility to the magnetic requirements at minimum mechanism mass.

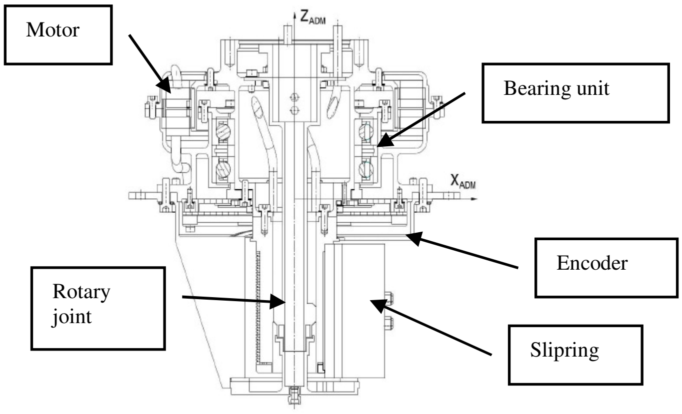


Fig.: 3 ADM Cross Section

Summarised, the ADM comprises the following main subassemblies:

- Mechanism Housing (Stainless Steel)
- Rotor shaft with I/F to Antenna S/S (Titanium)
- Bearing Unit ABEC9, Cronidur X30, Silicon Nitride balls, Polyamidimid (Torlon 4203) cage
- Lubrication Fomblin Z60, Bearing Preload at ambient conditions 1200 N
- Redundant Brushless DC Motor (independent Stators)
- Redundant Optical Encoder
- Contact-less RF Rotary Joint (supported by the ADM bearings)
- Slipring unit for power and signal transfer (to the HGA)

In the next figure an isometric view of the ADM is shown. On top of the mechanism the mechanical I/F to the Antenna can be seen, as well as the RF Waveguide I/F to the Antenna. At the side of the Waveguide, four slipring rotor harness bundles are depicted. On the bottom of the mechanism a SMA connector is provided for RF signal transfer.

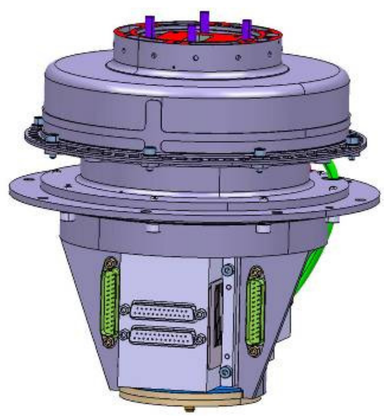


Fig.: 4 ADM Conceptual Design

3. KEY REQUIREMENTS

A short overview on important ADM requirements is listed below:

Requirement	Value	Comment
Pointing accuracy	< 0.05 deg over 100 s	Deviation from nominal velocity
Rotation velocity nominal	12 to 18 rpm	
Operational Temperature range	-15 to 80 deg C -15 to +115 deg C	On ADM Mounting I/F Flange On Antenna I/F
Magnetic field strength	<12.8 nT	At a sphere with radius 1 m from ADM (measured value)
Vibration levels	20 g sine 20.2 grms random	With a dummy mass of 6.5 kg on top at a distance of 95 mm from ADM I/F plane
Mass requirement	9.8 kg (7.9 kg achieved)	
Life	7 years cruise phase 1 year (goal 2 years) 10 million revs in orbit	Continuous operation
RF Frequency Range	Uplink 7.15 GHz Downlink 8.41 GHz	Power 25 W max
Insertion Loss	0.3 dB	
VSWR	1.25	
No. of Power /Signal Sliprings	33	
Overall Antenna Mass	20 kg	Antenna inertia 0.61 kgm2
Nominal operational ADM Power Consumption	8.6 W	ADM including ADMCE

Tab. 1 Requirements Overview

4. DEVELOPMENT RISK ASSESSMENT

At the beginning of the development the key driving requirements were identified and investigated in view of technical, schedule and development risk aspects. The importance of the individual requirements was judged and priorities were allocated. Four major design drivers were identified in view of technical criticality and development risk.

- *Thermal requirements*
  - Thermal mismatch, thermal compatibility to elevated temperatures, sensitivity to thermal gradients, limitation of encoder operation temperatures

- *Magnetic, EMC and Radiation requirements*
  - ADM and ADMCE design optimisation in view of Magnetic and EMC requirements
  - Provision of adequate radiation shielding for the optical encoder

- *Operation (and storage) Life*
  - Bearing Concept selection

- *Pointing/velocity error requirement (allowable position deviation per time increment)*
  - Controller Concept selection, controller optimisation and I/F to System controller

The other requirements are identified as lower level requirements which follow the above ones and do not jeopardize the design feasibility and mechanism performance.

The elevated operational temperature in combination with the requirement for continuous operation during mission at about 15 rpm was identified as critical. Therefore an important aspect was related to the selection of the Bearing unit including Cage material and lubrication concept and to the early verification of the ADM Bearing Unit.

Besides the Bearing, the slipring unit is the only additional element in the mechanism with a moving contact interface. Therefore in addition the slipring life had to be considered, however from the experience gained with sliprings on other similar scanning applications, this aspect was not addressed as a specific feasibility critical issue.

A very critical aspect was however seen in the applicability of the Optical Encoder at elevated temperatures. Therefore a two-fold effort was spent to confirm on the one hand the suitability of the Encoder EEE parts by means of a detailed thermal analysis on component level and to establish at the same time an ADM design minimising the encoder temperatures during operation by coupling the unit as close as possible to available heat sinks. The structural elements of the mechanism had to be optimised in view of thermal match, gradients and optimised heat fluxes in view of the encoder temperature limitation.

In addition, Parts and Materials selection had to be optimised to cope with the stringent magnetic and EMC requirements in order to minimise stray fluxes. Since the MMO mission is a magnetic mission, stray fields specifically produced by the ADM motor had to be mitigated. Therefore an important aspect was the magnetic analysis and the design optimisation of the ADM and of the ADM motors in view of magnetic aspects.

Especially in view of the ADMCE, the EMC requirements were judged extremely critical, so that high effort was spent to optimise the PCB layout and box design in view of these requirements.

A last but not less critical development aspect was given by the controller design realised in the FPGA of the ADMCE. In this context an early B/B model of the mechanism and of the electronics was built up in a functionally representative manner in order to allow early investigation of the control performance by means of a real time system and so to harmonise the I/F to the S/C control I/F provided by the customer.

5. RESULTING DESIGN APPROACH

5.1. Bearing Concept Verification

Considering the above findings it was mandatory to start at a very early stage of the project with the verification of the ADM bearing concept, since the bearings form the core element of the whole mechanism.

Therefore a bearing test stand was built up so to allow the test of the chosen bearing unit for friction torque over life under realistic thermal conditions in vacuum, with the correct pre-load and with representative surrounding materials and stiffness values.

One major decision point at the beginning of the bearing development was to identify whether liquid or dry lubrication should be selected as a baseline. Liquid lubricant provides smooth operation at low torque jitter and quite constant friction torque over time (important for the controller). It provides good lifetime and deletes the needs for purging during test and storage, while MoS2 would have been very compliant to the elevated temperature range.

A set of high precision inclined ball bearings from X30 steel with ceramic Si3N4 balls was procured off the shelf from FAG. The bearings were dismantled at Astrium and the Phenolic Resin cages which have a temperature limit at about 120 deg C (what is very marginal for the application) were exchanged and substituted by high temperature compatible Torlon 4203 Cages manufactured in house.

One set of bearings was lubricated with MoS2 at ESTL the other (baseline set) was liquid lubricated with high temperature synthetic oil Fomblin Z 60 which provides extremely low vapour pressure characteristics.
The bearing procurement and modification time up to start of friction and life test was extremely short and in the range of six weeks.

The bearings equipped with liquid lubrication (expected baseline) were mounted into flight representative housing and shaft interfaces (Representative shaft and housing materials compared to the later flight parts). At the beginning of the life test the friction torque influence at different rotation temperatures and rotation speeds was characterised.

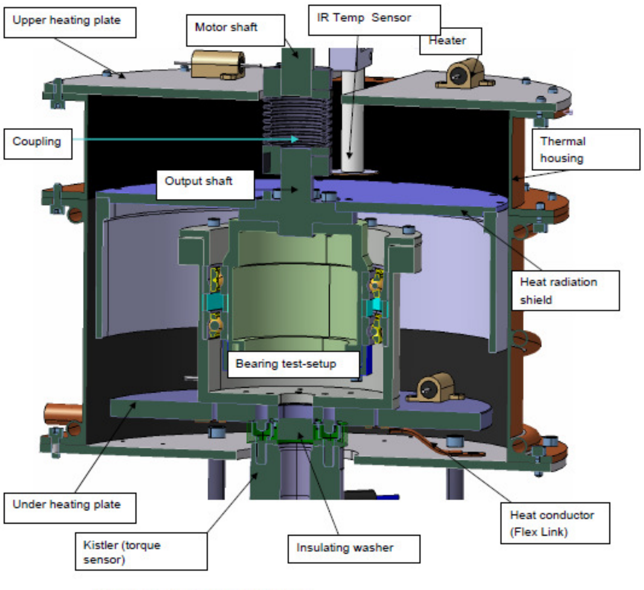


Fig.: 5 Flight Representative Bearing test stand and bearing configuration as used in the TV Test

The bearing life test was performed in a bearing test stand over 14.5 million revs corresponding to the worst case operation over 1 year including life margin without any significant change of friction over time.

An additionally performed gradient test applying the calculated gradient of 12 deg C between the rotating Shaft (Ti) and housing (Stainless Steel) yielded only marginally changed friction values since the ADM design is optimised for a wide thermal range at a nominal bearing pre-load of 1200 N.

At the nominal condition of high operation temperature, the slight thermal mismatch between rotating shaft and bearing housing yields a relaxation of the preload and thus a lower friction torque than at ambient conditions. This design feature yields an increased bearing life margin at the nominal high temperature operation regime. Summary of final torque measurement is shown in the next figure

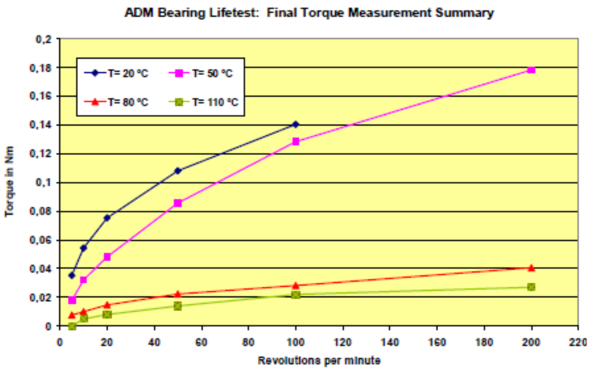


Fig.: 6 Friction Torque over rotation velocity at different temperatures (after 14 Million revs)

After test, the bearings were dismantled and inspected and their condition was still perfect. Based on the successful life test, the bearing concept was frozen and the liquid lubrication baseline was confirmed.

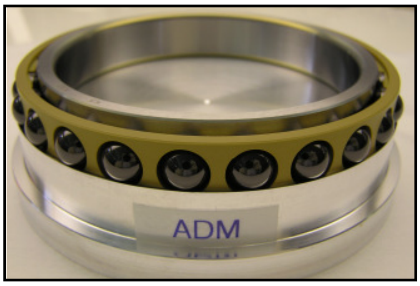


Fig.: 7 ADM Bearing, no degradation observed after Life test

5.2. Motor and Magnetic Requirements

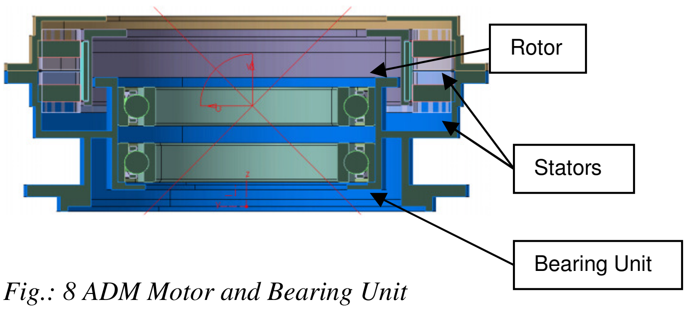


Fig.: 8 ADM Motor and Bearing Unit

The motor is a 3-Phase brushless DC motor and it includes two completely independent motor stators and one rotor equipped with rare earth magnets suitable for high temperature application.

Since the MMO mission is dedicated to the measurement of the Magnetic Characteristics of Mercury, the minimisation of the magnetic stray field produced by the ADM was identified as an important task. Such stray field reduction was performed by selecting the motor magnets according to their deviation in magnetic characteristics and by their subsequent well defined arrangement on the motor rotor. In addition, emphasis was laid to the rotor design itself and to the choice of adequate non-magnetic materials wherever possible. In addition the unit is demagnetised prior to delivery.

In order to cope with the stringent magnetic flux density requirements, a magnetic analysis was performed with Flux3D for the two motor stators and rotor including the ADM Housing. The magnetic flux density was calculated under different conditions: e.g. for un-powered and powered motor and with/ without housing for shielding.

The analysis demonstrated that the magnetic flux density requirement can be achieved by the baseline ADM design. However due to the extremely low magnetic flux density values to be calculated also the limits of the S/W capabilities were reached. In addition the calculation time for only one run took almost 80 h of calculation time though already the fastest available standard computer was used.

Special care was taken to the manufacturing process of the high temperature rare earth magnets. 724 magnets were manufactured and the magnetic moments of all this magnets were measured. Only magnets with a tolerance of >+/- 0.05% of the magnetic moment compared to the nominal value were selected for the PFM ADM in order to reduce residual external stray fields to a minimum.

5.3. Rotary Joint

Since the Waveguide flange I/F at the hot end of the RJ which is the I/F to the Antenna side would bring excessive heat flow into the mechanism, an interface Waveguide adapter is used which consists of a silver coated Titanium Wave guide part acting as an isolator. This Isolator Waveguide is interfacing the Rotary Joint manufactured from Aluminium in the transition from rectangular to circular cross section.

The contact-less X-Band RF Rotary Joint (7.1 to 8.5 GHz) carries no own bearings and is supported by the ADM main bearing. This design avoids the chance of increased friction or bearing damage at elevated temperatures due to mechanical or thermal mismatch.

The design and measured RF performance of the Rotary Joint are shown in the following figures. The RF performance was measured at ambient and in addition at high temperature conditions.

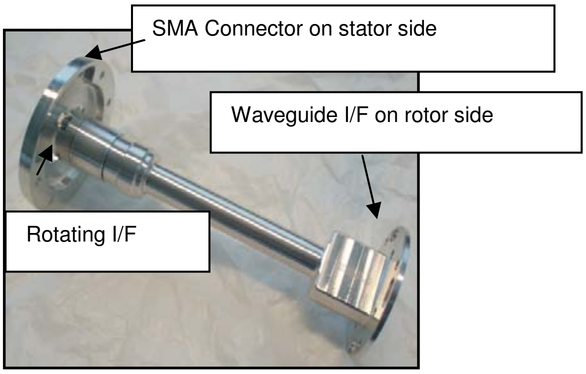


Fig.: 9 RF Rotary Joint

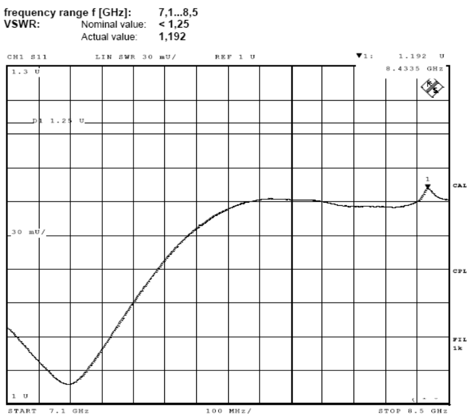


Fig.: 10 Rotary joint RF Performance at 110 deg C

5.4. Optical Encoder

The redundant optical encoder used for position feedback is of the incremental type with a resolution of 16 bits. Absolute reference is provided by one additional signal per turn. The encoder was successfully tested on component level at the maximum temperatures and detailed thermal analysis was performed on parts level in order to verify its suitability for the application.

6. CONTROL ELECTRONICS (ADMCE)

6.1. Design Overview

The ADMCE consists of a fully cold redundant electronics unit housed in one mechanical box. The separation between the main and redundant electronics is in its vertical plane which allows the best thermal connection of both units to the thermal interface. In addition, this arrangement provides the minimum volume due to the high density within the ADMCE housing (270x230x 57mm).

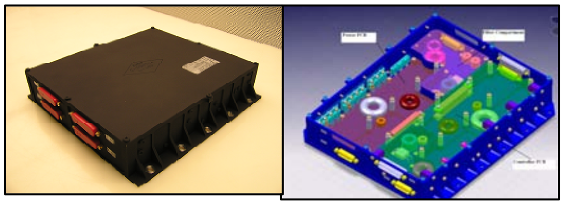


Fig.: 11 ADMCE Housing and PCB Arrangement

6.2. ADMCE Design Drivers

The major design-driving requirements for the Control Electronics had been identified as follows

- ADMCE mass/volume
- Thermal Interface temperature requirements
- EMC Requirements
- Velocity Control Loop Accuracy and Stability

The ADMCE has been optimized for volume by the arrangement of the PCBs parallel to the interface plate. Also, when performing the trade-off on controller architecture (see below), the volume criteria played an important role

The ADMCE housing has been designed as an integral shell carrying all printed circuit boards and cooling angles directly. This design minimizes the number of mechanical contact areas between heat dissipating components and ADMCE thermal interface. Further side effects of this design are the better electrical bonding conditions improving EMC behaviour and the high structural stiffness of the construction.

6.3. EMC Requirements

Based on the scientific needs of a Magnetospheric mission, high effort has been spent during the definition and the design of the ADMCE regarding its compliance to the very stringent EMC requirements. Several measures have contributed to the EMC characteristics of the ADM/ADMCE system:

- Crystal stabilized DC/DC converter
- Capacitive de-coupling of all power transistors from housing but maintaining low thermal resistance to housing
- Box-Construction with placement of EMC-Input Filter in separate mechanical compartment eliminating all noise coupling to input lines.

- Close regard on PCB layout as well as simulation of EMC behaviour of critical electrical routing in the layout phase
- Dual-stage filtering of motor current output to ADM

7. VELOCITY CONTROL LOOP

7.1. Controller Trade-off

The controller plays a key role for the achievement of the required highly precise rotation velocity to be adjusted to the S/C rotation rate of between 12 to 18 rpm at a required maximum deviation of +/- 0.05 deg over 100 s. It is included in the ADMCE with an I/F to the additional superimposed low bandwidth position controller on MMO System side controlling the S/C rotation rate.

A major Trade-Off has been performed comparing a µ-Processor based controller versus a FPGA based (VHDL-coded) velocity control loop.

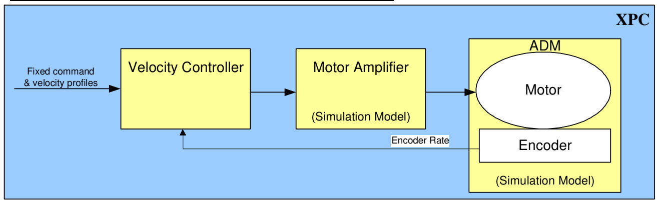
A µ-Processor solution for velocity control would consist of a fixed point 16-bit µ-Controller performing the control loop calculations. This approach provides high flexibility (S/W) but also high complexity, power consumption, volume and mass and low processing performance when float variables are required. In addition the transfer from Simulink simulation to controller S/W is not reliable

For the FPGA based solution, one single FPGA performs the full control task. It has to be mentioned that one FPGA is required within the ADMCE anyway for interface handling and serial/parallel conversion purposes, which leaves about 70% of its capacity to perform control tasks. For the application the reliable transfer from the Simulink model to the VHDL model is of key importance. The only drawback for this approach is the low design flexibility at a late stage of development. The FPGA based controller concept should be clearly selected as baseline.

7.2. Controller Development Approach

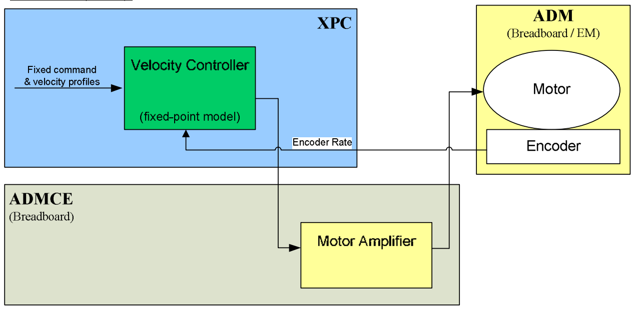
For the design and validation of the velocity controller, a stepwise approach from the first simulation down to the final validation of the controller in FPGA hardware has been defined.
This design cycle allows the proper verification of each intermediate step before progressing to the next design step. The clear advantage of this approach was that the complete controller architecture, parameter development and validation could be performed in a highly flexible simulation environment. During the conversion from simulation to hardware, the FPGA-based controller behaved absolutely identical to the simulation results. The applied controller design cycle is shown in the following sequence:

Generation of full simulation model



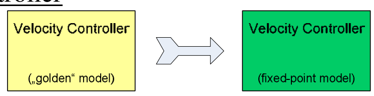
Objective: Evolution of control architecture/parameters
Tasks: Establish simulation environment on XPC. Define control architecture. Adapt motor- and controller models
Result: Flexible system simulation environment

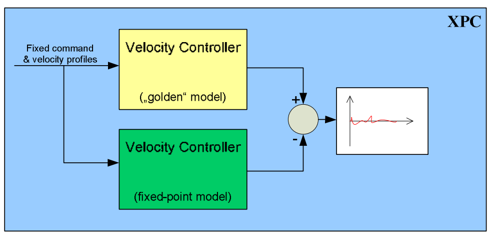
Integration of ADMCE (BB) motor amplifier and ADM (BB)



Objective: Full system verification of the ideal control performance. Simulation Model Verification and fine tuning
Tasks: Integrate real motor amplifiers and real mechanism to development environment. Optimize control parameters and check performance.
Result: Ideal velocity control model ("golden" model). This ideal model runs with ideal variables (double precision) and without any later H/W limitations. End to end Control performance demonstration.

Transfer of ideal ("golden") controller to fixed-point controller

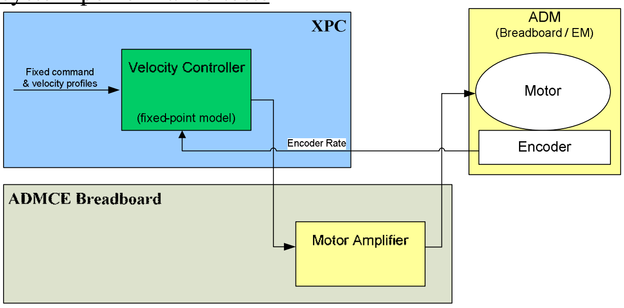




Objective: Generation of a velocity controller, fully basing on fixed-point arithmetic

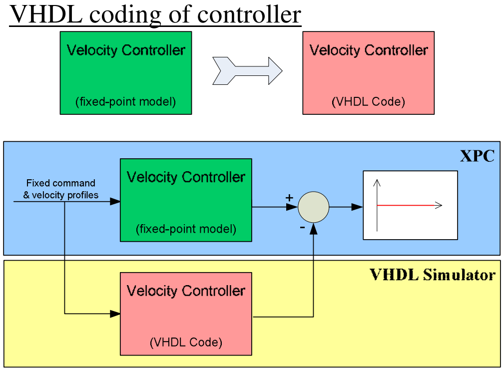
Tasks: Transfer ideal controller to fixed-point. Adjust fixed-point variable length and resolution to achieve identical behaviour
Result: Fixed point arithmetic controller. Time-based verification against "golden" model

Verification of fixed-point arithmetic controller in system performance tests



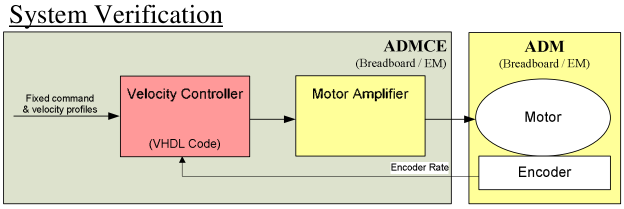
Tasks: Performance tests with fixed-point controller
Objective: Validate controller performance before transfer to hardware
Result: Validated and Performance tested fixed-point controller

VHDL coding of controller



Task: Generation of VHDL code (FPGA source code) and Co-Simulation of fixed-point controller with VHDL behaviour

System Verification



Tasks: Carry out performance tests
Result: End to end verification of ADM/ADMCE system. Fully identical behaviour of early simulation models with final hardware

8. LESSONS LEARNT

A requirement analysis performed at the beginning of the design Phase in view associated development risks turned out to be extremely helpful for the project.
Good experience was made with the procurement of high precision off the shelf bearings and the in-house definition and implementation of cages and lubrication. This approach saves significantly procurement time and thus allows early verification of the chosen bearing concept under realistic test conditions so to mitigate the development risk.

Good high temperature performance of the X30 bearings equipped with ceramic balls and Torlon cages in combination with Fomblin Z60 high temperature synthetic oil.

The optimisation of the design in view of thermal conditions and the identification of passive thermal control measures allowed increase of margin for temperature critical parts (encoders).

The early consideration of the Electronics and Mechanism design in view of the stringent EMC respectively Magnetics requirement was of key importance.

Compared to transfer of theoretical models to software/hardware with subsequent fine-tuning to the 'real world'-conditions, the chosen controller design flow with clear check possibilities and success criteria for each development step was of key advantage regarding the stringent operation stability requirements

The final controller in hardware was optimized with regard to FPGA logic-gate budgets and it was demonstrated that even control architectures of high complexity can be accommodated in a Processor-less architecture.