EMI CONTROL IN THE PRESENCE OF COMPOSITES MATERIALS

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OVERVIEW

In the scope of this paper the development of an EM-seal ultra lightweight CFRP housing is presented which is aimed for specific space missions with high mass restrict-tions. Based on a sample test program including carbon nanotube based composite materials and CFRP/CFRP joints, a CFRP electronic housing was created which features optimum EM performance in combination with a simple and modular design concept. As a reference the SUMER Digital Processing Unit aboard the SOHO spaceborne solar observatory was chosen. This reference housing is an ultra light integrally milled electronic housing from AL-alloy. The composite housing was developed with the goal to achieve the same mechanical, thermal and electromagnetic performance as the AL-housing but with less mass. Additional benefits are the compatibility in thermal expansion of the housing to the satellite structure. Measurements proved that the combination of a conductive matrix, achieved by carbon nano tubes, highly conductive carbon fibres and a design incorporating electromagnetic interference (EMI) aspects from the very beginning, results in a housing with comparable EM characteristics as the metal reference housing even without additional shielding as e.g. metal plating. The predicted weight savings could be achieved.

1. INTRODUCTION

Composite materials like CFRP are in widespread use on spacecraft structures, mainly for sandwich panels. They combine a very high stiffness with low weight and a very low coefficient of thermal extension (CTE). For electronic housings usually aluminium is used as structural material, especially because of the well known electromagnetic properties and the comparatively cheap manufacturing. In the presence of CFRP, EMI control is currently achieved by separate means like e.g. grounding rails or metallic electronic enclosures. However especially interplanetary missions demand for further weight savings which can be achieved if the electromagnetic properties of CFRP materials are used in an EMI aware CFRP design. Furthermore a compatibility in the CTE of the structural material of the sandwich panels and the electronic housings mounted onto them can be achieved. This was the motivation for ESA to contract the German company HPS GmbH with the Technology Research Programme (TRP) study A0/1-4613/04/NL/JA on “Spacecraft EMI Control in the Presence of Composite Materials”. While this paper is focused on the design of an ultralightweight CFRP electronic box, the TRP study also covered aspects of modelling CFRP materials, an extensive sample testing program on the shielding effectiveness, common mode impedance measurements and simulations on two wire configurations above metallic (grounding rails) and different CFRP structures as well as a study on the fault current capabilities of CFRP and ways to electrically bond inserts.

2. EMI ASPECTS OF CFRP

With regard to EMI aspects CFRP as a highly anisotropic material behaves different to metal. While the electrical conductivity along the fibres is fairly good (around one thousandth of metals), the conductivity in a direction perpendicular to the fibres varies strongly with the manufacturing methods (fibre volume content) from almost zero to values substantially lower than along the fibres. Things get even worse, when layers of prepregs or fabric are stacked. The conductivity in a direction out of plane of the laminate is almost undefined and in all cases much lower than in the other directions.

Due to the low overall conductivity compared to metal, the skin depth δ, which is a measure for the depth in which significant currents are induced by the incident electromagnetic radiation

$$\delta = \frac{1}{\sqrt{\sigma \pi \mu f}} \tag{1}$$

is increased.

We can see that for high frequencies f and high values of conductivity σ and permeability μ the skin depths gets small. This keeps induced currents from penetrating into deeper regions of a wall if frequency and conductivity is high as in the case of RF and metallic skins.

However with the superior mechanical properties of CFRP which result in lower wall thicknesses, the skin depth of CFRP structures is in the range of their wall thickness as shown in TAB. 1.

Frequency	δ copper	δ CFRP
60 Hz	8.57 mm	271 mm
10 kHz	0.66 mm	21 mm
10 MHz	21 µm	0,66 mm

TAB. 1 Skin depth of CFRP and copper

To overcome the problem with the low conductivity, several measures can be taken:

- Increasing the conductivity of the CFRP laminate
- Application of highly conductive layers e.g. metalised carbon fibres
- Metalisation of the CFRP surface
- Separate metal layers
- Internal metal layers embedded in the laminate e.g. tungsten or tantalum in case of need for additional radiation shielding.

2.1. EMI Aspects of CFRP Bolted Joints

The very low electrical conductivity out of plane of CFRP materials creates special problems with bolted joints. The joints act like a slot antenna, so the shielding efficiency is dramatically reduced. Tests have been conducted by NPL using a waveguide measurement setup.

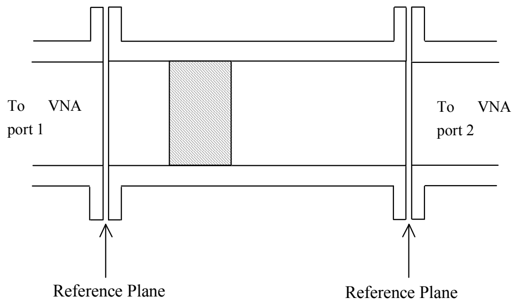


FIG. 1 Waveguide measurement of shielding efficiency. The test sample is shown hatched.

FIG. 2 shows a sample for waveguide measurements, which was modified with a joint of different configurations:

- Joint 0: without the cover in place
- Joint 1: cover screwed to the specimen
- Joint 2: cover screwed to the specimen and a silver paint connection between cover and specimen
- Joint 3: cover screwed to the specimen and a silver paint connection between cover and specimen and a silver paint connection between the screws and specimen.

The shielding efficiency SE of the sample drops about 70 dB when the fibres were cut by a slot in the centre of the sample (“No joint”) When the slot is covered by a lid of the same material as the original sample, the loss in shielding efficiency is reduced to around 12 to 15 dB depending on the usage of conductive glue underneath the screws.

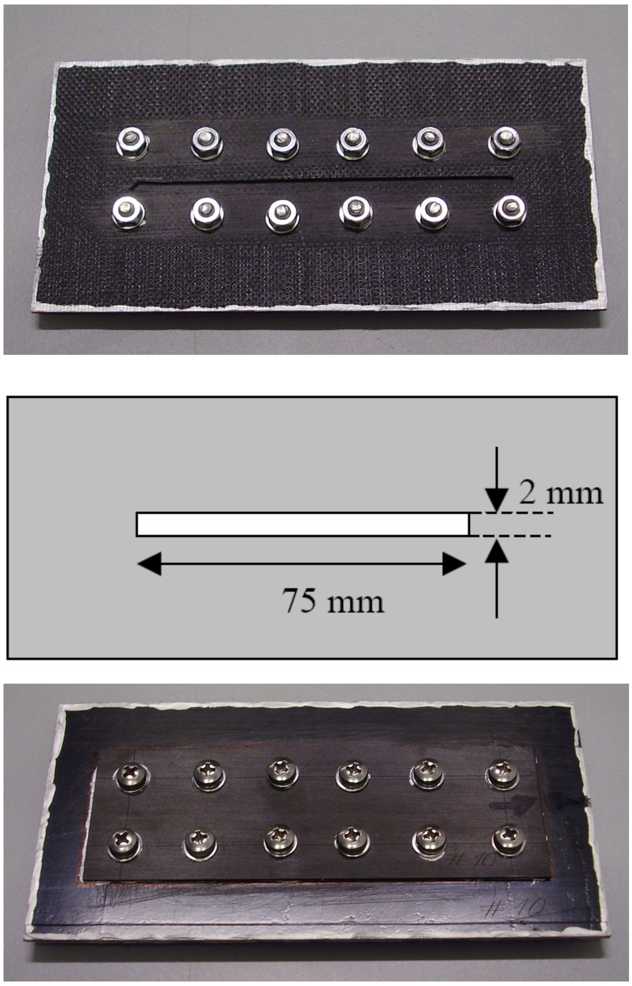


FIG. 2 Bolted joint shielding efficiency test sample

	No gap	Joint 0	Joint 1	Joint 2	Joint 3
Frequency GHz	SE (dB)	SE (dB)	SE (dB)	SE (dB)	SE (dB)
1.7	-73.5	-4.8	-55.3	-58.1	-58.1
1.8	-73.4	-2.7	-54.7	-57.8	-58.7
1.9	-72.9	-1.6	-54.1	-57.3	-58.2
2.0	-72.7	-1.7	-53.7	-57.0	-58.0
2.6	-73.2	-7.8	-54.1	-58.2	-59.1

TAB. 2 Shielding efficiency under the influence of a slot covered with a bolted lid.

3. EMI-INTEGRATED CFRP DESIGN

Because of the strongly anisotropic nature of the electric properties of CFRP material, a successful design of EMI relevant components has to incorporate these aspects from the very beginning. EMI aspects influences the design in many ways:

- Selection of material
  - Fibres with high electrical conductivity
  - Conductive matrix systems (e.g. equipped with carbon nano tubes, see FIG. 3)
  - Metallised carbon fibres
- Basic layout
  - Avoidance of joints where possible
  - Large overlaps
  - Fibre winding (endless fibres rather than patches)
- Fibre orientation (Shielding efficiency of unidirectional CFRP is dependent on polarisation of incident wave)
- Contacting of highly conductive fibre ends (see FIG. 4)
  - With conductive glue
  - With metal deposition

In case of electronic housings, the selection of the material is driven by the conductivity of the laminate rather than its strength. There are two ways to increase the conductivity of composite materials:

1. Usage of highly conductive carbon fibres.
2. Usage of a conductive matrix system.

In case of the new CFRP housing both methods have been used. As material for the main body a K13C2U high stiffness carbon fibre with very good electrical and thermal conductivity was used. For the matrix, a carbon nano tube (CNT) modified resin system was used, further enhancing the conductivity of the composite.

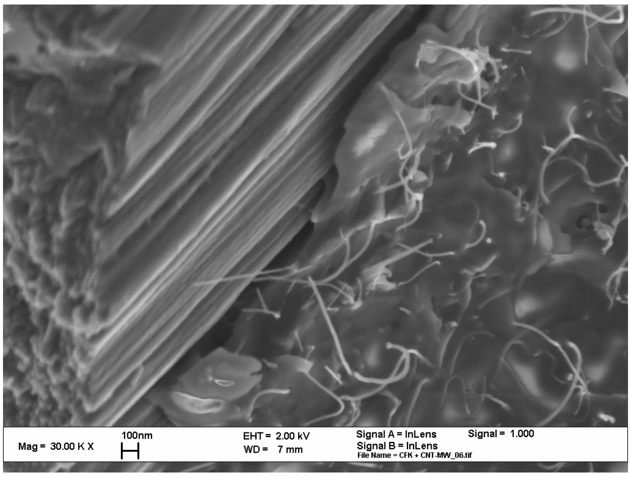


FIG. 3 Electron microscopic photo of a carbon fibre (left side) and a CNT modified epoxy matrix

FIG. 4 shows an electromagnetically seal CFRP bolted joint where a layer of copper is applied to achieve good electrical bonding.

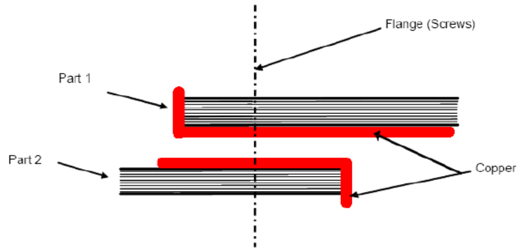


FIG. 4 Electrically seal bolted joint

4. CFRP ELECTRONIC BOX

One goal of the ESA study was the development of a lightweight electronic box, which should show substantial weight benefits compared to a metal reference box without cutbacks on the EM shielding.

4.1. Selection of a Reference Housing

As a reference housing an ultralightweight Al electronic box was chosen, which was manufactured by Kayser-Threde GmbH to accommodate the data processing unit (DPU) of the SUMER experiment on the SOHO solar observatory satellite. The cuboid shape of this medium sized metallic box is representative to many applications. The mass requirements have been extreme due to the orbit around the sun. The box is made from Al sheet metal and integrally milled base and frame parts which have been milled down to a minimum wall thickness of only 0.5 mm. The very high restrictions on the mass of the electronic housing justify the expected higher costs of CFRP housings.

FIG. 5 shows the aluminium reference box (left side) together with the new developed CFRP box. The reference box contains ten rectangular printed circuit boards (PCBs) and carries two piggyback type sub housings on one side (not shown on the picture). This payload has got a mass of 7.5 kg including the connectors. The PCBs are connected via a backplane and fixed by form fit achieved by grooves in the milled parts of the housing (FIG. 6). One PCB carrying the DC/DC converters is bolted onto the side wall, thus ensuring good thermal conductivity. The PCBs produce a maximum of 13.5 W which is drained by conductivity and radiation.

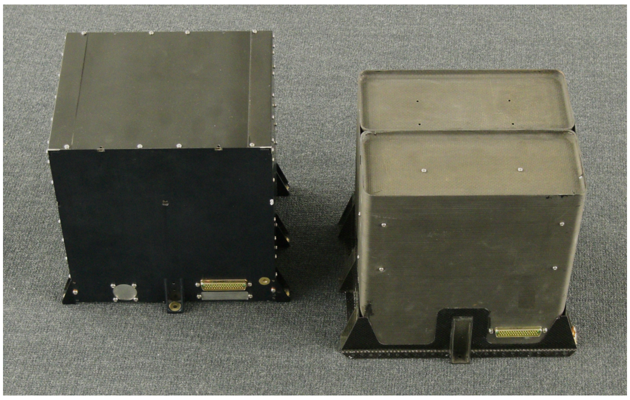


FIG. 5 The CFRP (right) and the AL reference electronic box

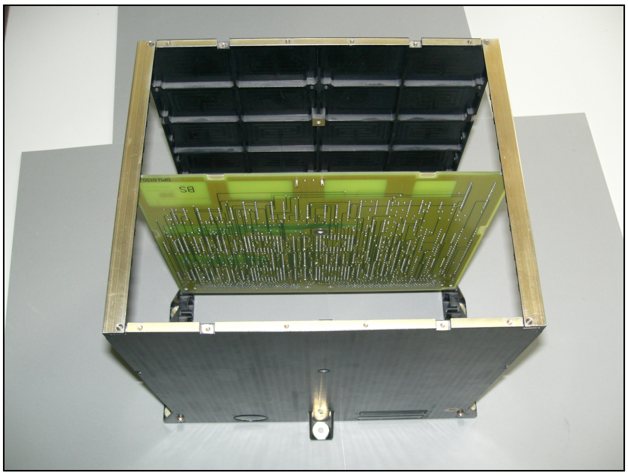


FIG. 6 SUMER DPU electronic housing, sheet metal panels removed

4.2. Design and Manufacturing of an Ultralight CFRP Electronic Box

The design was driven by the following basic requirements:

- Ultra lightweight performance
- EM leak tightness
- Scalability:
  - The box concept should cover small single PCB to large multi-PCB / Backplane applications.
  - Scalability should be achieved with a minimum of non recurring costs (moulds).
  - Scalability is not restricted to the size, it also comprises the ability to carry different payload masses.
- Thermal performance
- Low manufacturing costs
  - Moulds and rigs
  - Easy assembly

The specific requirements on loads and mechanical sizes have been taken from the requirements of the reference housing.

The overall layout was equally driven by mechanical, thermal, manufacturing and EMI aspects. Lightweight performance is primarily achieved by design rather than the choice of materials, so for the CFRP box a single shell design with thin walls was chosen. To achieve a high degree of scalability, the basic layout consists of cuboid shaped chambers with rounded edges which contain the printed circuit boards. A top cover and a reinforcement angle with feet at the bottom complete the box. The cells are produced by an automated filament winding process as tubes of rectangular cross section which can be cut to the desired length. Due to the production process, the inner surface of the cells is defined with very low dimensional tolerances. The thickness of the wall and the fibre orientation can be varied easily by the winding parameters to match different mechanical, thermal or shielding requirements. Highly thermally and electrically conductive K-13C2U fibres are used for the main bodies. The other parts have been manufactured from HTA carbon fibre and a nickel coated non woven carbon fibre mat is used as an additional shielding layer on the top covers (FIG. 9).

The lower end of the box, which is flanged to the supporting structure is closed with a flat cover. FIG. 7 shows this concept on a box with two chambers which are closed by two covers. A thin flange made from an angular part of CFRP is running around the bottom. This flange serves as an EM seal and allows the attachment for the bottom cover. The PCBs are rested on the backplane (not shown) and fixed to the wall.

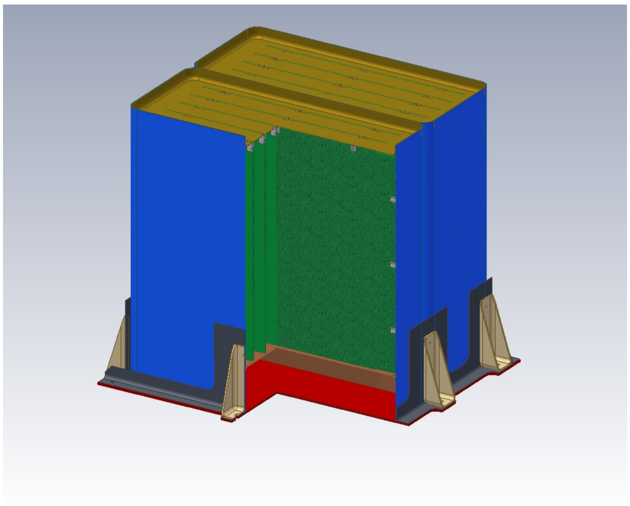


FIG. 7 CAD model of the housing

4.3. Fixation of PCBs to the Housing

The fixation of the PCBs inside the electronic housing is achieved by simple brackets which are riveted onto the PCB and which supply a fixation thread. Six of the brackets are used for fixing one PCB. Besides the mechanical load path these brackets also supply a thermal and an electrical path to the housing walls. This design was chosen to keep the electronic housing as simple as possible. Usually some kind of rails or form fit in slots as in the reference housing is used, but these methods are not adequate to CFRP structures. In case of components with high power loss, these components can be situated directly on an enlarged bracket, thus eliminating the thermal resistances of the component to the PCB.

Another aspect of this way to fix the PCBs is the fact, that on the wall of the housing small buckling areas are created which is relevant to the thin walls of the housing in combination with the abandonment of any sandwich structure.

The drawback of this method is the enhanced time and effort in mounting the PCBs compared to fixation via slots, but this is not relevant for satellite electronics, which are usually mounted once and no maintenance is foreseen.

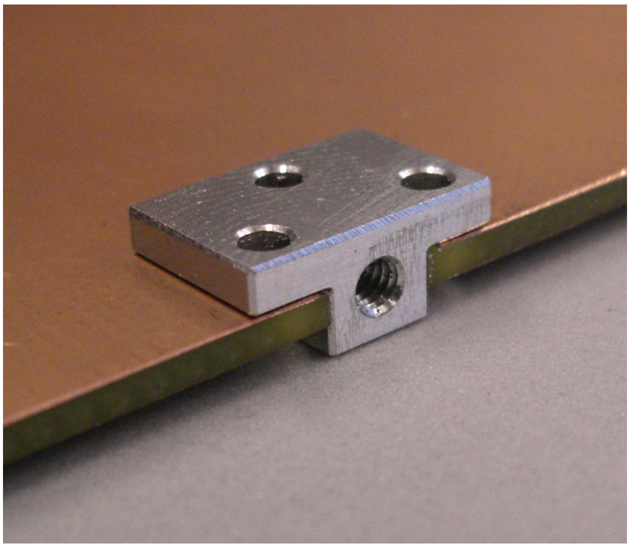


FIG. 8 PCB fixation bracket (to be riveted onto the PCB)

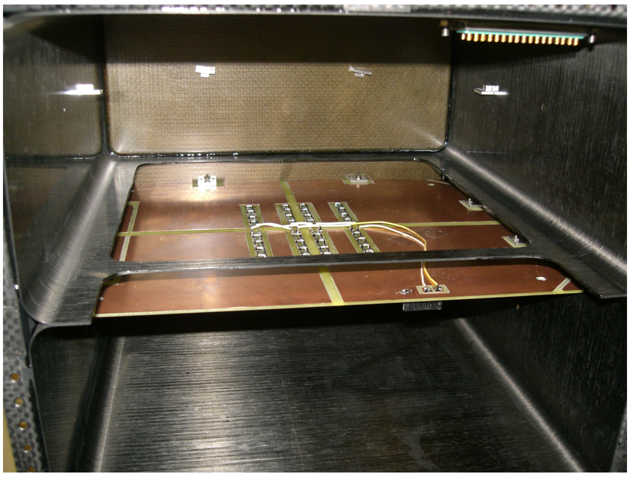


FIG. 9 Dummy PCB fixed with brackets in the CFRP housing. The centre wall between the cells was partly removed to create an electrically identical cavity as in the reference housing. The nickel coated carbon fibre mat is visible on the top cover of the housing.

Special attention was paid to the joints. For the bonded joint of the top cover a carbon nano tube modified glue was used which not only provided mechanical strength but also electrical conductivity. The bolted joint used for the bottom cover was carried out with small spacing and countersunk screws (FIG. 10) which give good electrical conductiv

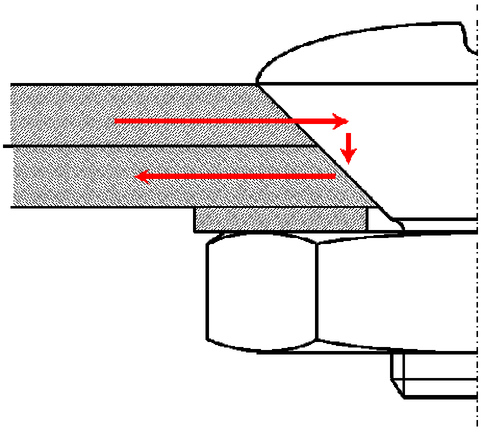


FIG. 10 Current path from bottom CFRP lid to CFRP flange via countersunk bolted joint (CFRP lid and flange are shown shaded.)

5. BONDING MEASUREMENTS

Bonding measurements were done using a four wire method between various PCB brackets. Two configurations have been tested: One configuration with metal plating on the top rim and one with untreated case parts. The metal plating of the rim dramatically reduced the resistance from the rectangular chamber walls to the top lids.

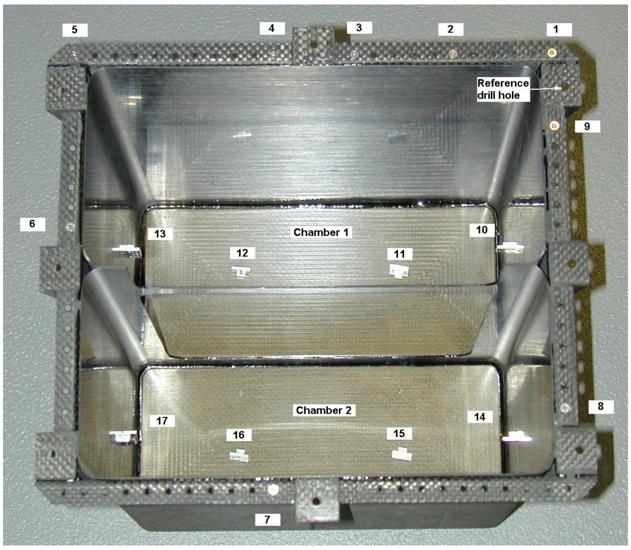


FIG. 11 View inside the CFRP case with points of bonding measurements

A significant difference in the conductivity of the surfaces of the cuboid chambers was noticeable: While the inner surface showed good conductivity, the outer surface which was originally covered with a peel-ply showed almost none. It is supposed that the peel ply leaves a non conductive surface of resin while the fibres touch the surface in case of the inner side of the wall.

Un-treated case parts		
Measured across	**4-wire test method / test current 20 mA**	**Value in Ohm**
Point 10 to point 11	Chamber wall 1 to cover 1	42.7
Point 12 to point 13	Chamber wall 1 to cover 1	41.7
Point 14 to point 15	Chamber wall 2 to cover 2	13.1
Point 16 to point 17	Chamber wall 2 to cover 2	13
Point 13 to point 17	Chamber wall 1 to wall 2	44.3
Point 10 to point 14	Chamber wall 1 to wall 2	44.3

TAB. 3 Bonding measurements of different parts of the CFRP housing (without metalized edges)

Since these bonding properties may have a negative influence on the shielding efficiency of a CFRP case the bonding resistances of the joints were reduced prior to the further tests. This was done by galvanizing the main edges of the CFRP case with a thin copper layer. The evaluation of the results summarized in TAB. 3 and TAB. 4 show that the bonding resistance between two adjacent case parts is reduced by a factor of up to 3000!

Galvanizes edges on top and side walls		
Measured across	**4-wire test method / test current 52 mA**	**Value in Ohm**
Point 10 to point 11	Chamber wall 1 to cover 1	0.041
Point 14 to point 15	Chamber wall 2 to cover 2	0.041
Point 10 to point 14	Chamber wall 1 to wall 2	0.013
Point 11 to point 15	Cover 1 to cover 2	0.1

TAB. 4 Bonding measurements with metalized top edges of the CFRP housing

6. ELECTROMAGNETIC SHIELDING EFFICIENCY TESTS

The CFRP housing and the AL reference housing have been EM tested in comparison to each other at the premises of SERCO / Ottobrunn. For this purpose they have been equipped with dummy boards which provide the thermal loads and the noise of typical DC/DC-converters as well as a microcontroller.

FIG. 12 Reference measurements without case

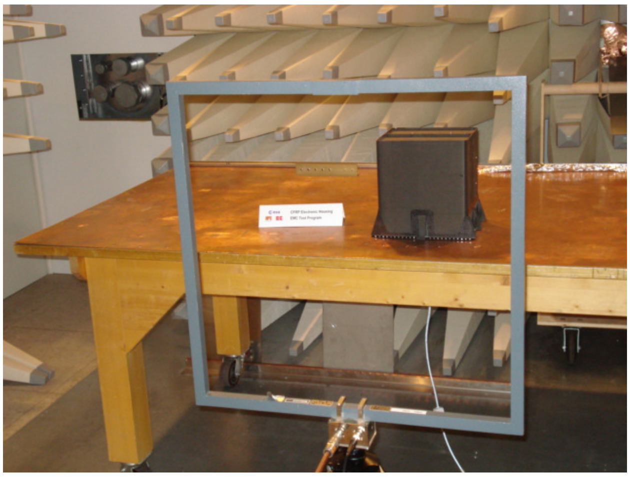


FIG. 13 CFRP electronic housing in the test chamber

6.1. Shielding of Magnetic Fields

For the destination of the magnetic shielding a loop antenna has been situated inside the housing, which was connected to a cable that was routed through the case under test as well as through the wall of the test chamber to an EMI receiver. The emitting antenna as well as the receiving antenna were positioned in the way that the planes of the loops were oriented parallel to each other. This orientation provides a worst case coupling condition. While a fixed rf power was injected into the transmitting antenna the signal at the output of the receiving antenna was measured in three configurations:

- Loop antenna without case
- Loop antenna inside aluminium case
- Loop antenna inside CFRP case.

The test without loop antenna (FIG. 12) served as a reference for the determination of the magnetic shielding efficiency.

FIG. 14 shows the magnetic shielding efficiency of the aluminium case in comparison to the CFRP case. The evaluation of the results show that the CFRP case has a negligible attenuation against magnetic fields for frequencies in the lower kHz range. Up to 2 MHz the attenuation of the CFRP case is about 30 dB lower than the magnetic shielding efficiency of the aluminium case. Above 2 MHz the magnetic shielding efficiency of CFRP seems to become independent from the frequency. The results for the aluminium case above 10 MHz look strange and are probably not realistic. For frequencies between 10 MHz and 30 MHz resonance effects between the test chamber and the test setup occur and cause high currents flow along the cable screens. The measurement equipment picked up interference signals via the cable screen so that the real signal coming from the antenna could not longer be determined from the noise level.

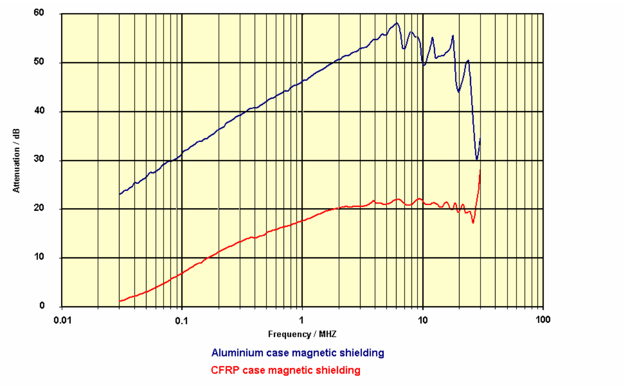


FIG. 14 Magnetic shielding efficiency of the aluminium and the CFRP case

6.2. Shielding against Electromagnetic Fields

The electromagnetic field was generated by suitable antennae. On the test table the equipment under test was mounted in the same manner as it has been done for the test configurations of the magnetic shielding test. The load board 2 without the loop antenna was inside the case under test. The field inside the case was measured by a rod antenna. Four different equipment configurations were tested:

- Rod antenna on the test table without case as a reference measurement
- Rod antenna inside the aluminium case
- Rod antenna inside the CFRP case (copper plated edges)
- Rod antenna inside the CFRP case (copper layer removed from edges).

The CFRP case was irradiated from two different sides. The irradiation from the +z side was representative for the configuration comparable to the aluminium case and the irradiation from the –y side was selected additionally because on this side the long vertical joint between the two case parts was facing directly the transmitting antenna.

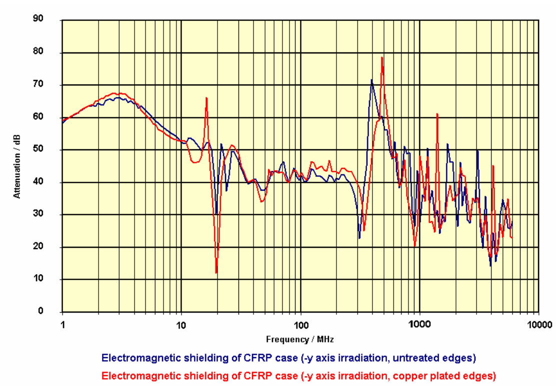
The following configurations were compared to each other:

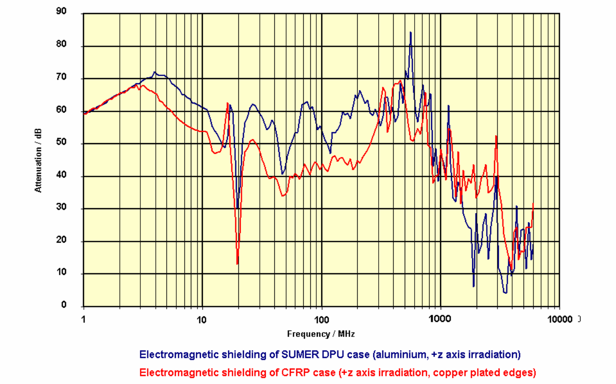
- CFRP case to aluminium reference case
- CFRP case with copper plated edges irradiated from two representative directions
- CFRP case with copper plated edges to CFRP case without edge treatment (two representative directions)
- CFRP case without copper plated edges irradiated from two representative directions.

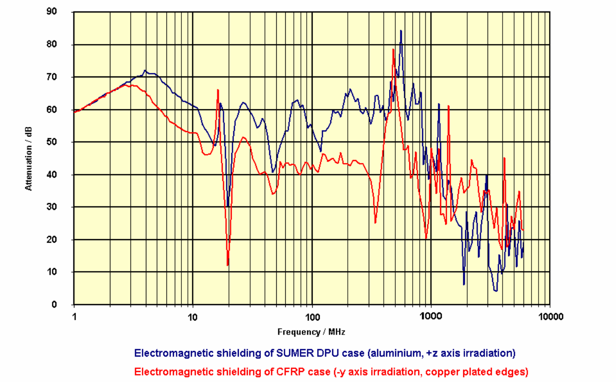
The analysis of the diagrams give the following results:

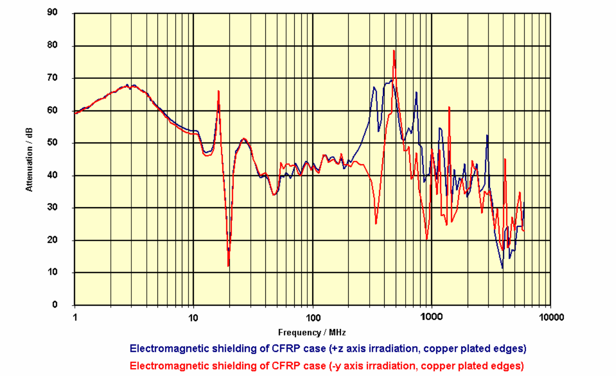
- From 3 MHz to 800 MHz the shielding efficiency of the CFRP case is 10 to 20 dB lower than the shielding efficiency of the aluminium case. Above 1.5 GHz the shielding efficiency of the CFRP case is 10 to 20 dB better than the shielding efficiency of the aluminium case. This effect is probably caused by the fact that the different parts of the aluminium case are fixed together by screws that give a contact at the locations of the screws only. As soon as the distance between two screws is equal to the half of a wavelength the slot acts as an antenna and decreases the attenuation to zero. The distance between two screws varied between 2.5 cm and 3.0 cm for the SUMER DPU case. This gives a theoretical cut-off frequency of 5 to 6 GHz. In practice, the attenuation of the aluminium case decreases below the cut-off frequency because there are a lot of slots which are no longer small compared to the wavelength.
- The comparison between the shielding efficiency of the CFRP case irradiated from the flat +z face to the values received from the irradiation from a face where a long vertical joint (-y face) was illuminated by the incident field gives a significant difference between 200 MHz and 2 GHz.
- In general, the attenuation is a little bit higher as long as the edges at the major joints are covered by a metal layer that gives a good contact between the fibres. The difference, however, is not higher than 10 dB.
- The aluminium case was tested in +z direction only because this is the worst case direction for the present design of the aluminium case. In +z direction, the slots between the aluminium frame and the cover plates are illuminated directly and they will act as slot antennae.
- In order to compare the worst case conditions for both case types the aluminium case irradiated from +z direction has to be compared to the CFRP case irradiated from the -y direction.

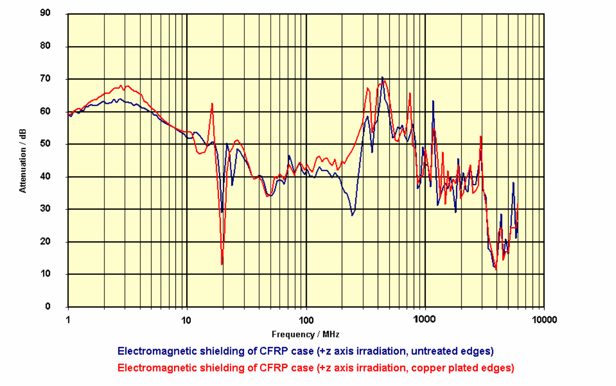
All measurements show a deep drop of the attenuation slightly below 20 MHz. This is not typical for both cases. It seems to be a measurement error because it is known that the test chamber exhibits a resonance around this frequency. The measurement plots show resonance effects at slightly different resonance frequencies between 10 MHz and 30 MHz (see para. 5.1). Therefore, the calculated shielding efficiency value has a large measurement uncertainty in this frequency range.











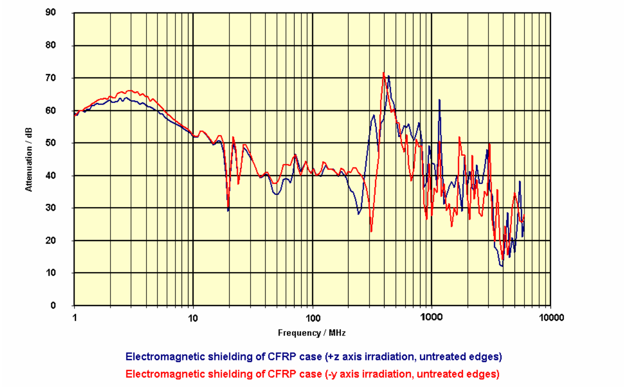


FIG. 15 Comparison of CFRP and metal reference housing

6.2.1. Final Conclusion

An aluminium case has a magnetic shielding efficiency that is some 30 dB better than the shielding efficiency of a CFRP case. The magnetic shielding efficiency is highly dependant from the electrical conductivity as long as the thickness of the case wall is smaller than the effective skin depth for currents induced by the incident magnetic field. The influence of joints may also be significant since it can have a great influence on the integrated resistance along the unit's circumference.

The electromagnetic shielding efficiency of both case materials are comparable. The tested aluminium case is approximately 10 dB better up to frequencies of about 300 MHz. In the GHz range the CFRP case is roughly 10 dB better than the aluminium case because there are no screwed joints that act as slot antennae. The electromagnetic shielding efficiency is apparently not significantly influenced by the high overall contact resistance between two adjacent parts of the CFRP case. The joint bonded with carbon nanotube filled adhesive acts as a distributed joint with certain attenuation properties at high frequencies. Electromagnetic fields that penetrate the slot are obviously attenuated by the dissipative components inside the adhesive.

With the new CFRP design substantial weight savings of approx 20% have been achieved even compared to the ultralightweight metal design of the original SUMER DPU housing. Compared to standard space electronic housings weight savings of 30% and more can be achieved.

7. REFERENCES

ESA TEC-EEE: Statement of Work “Spacecraft EMI Control in the Presence of Composite Materials” TEC-EEE/2003.122 Iss1 23.04.2004