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Train carbody EMC shielding measurement

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***Abstract* – The aim of this project is to verify the magnetic field shielding effectiveness of the carbody of a Bombardier Transportation's distributed power train in order to preliminary establish the value of the magnetic field inside the train knowing the emission values of the electrical equipments installed in the underframe. Both simulations and measurement of the shielding effectiveness were carried out, which have led to slight different values. A secondary aim of this project is to understand the causes of these differences.**

I. INTRODUCTION

The design of a new train is a very complex work that involves several engineering disciplines; it starts from a first design phase that fixes the technical requirements and the preliminary concept (technical characteristics that the new train shall have) and continues with successive phases of detailed design.

One important step of this complex work is the EMC design; by knowing the EMC field limits fixed by the Standards the goal of the EMC engineer is to preliminary check, by doing proper calculations and assumptions, if the values of the EMC field inside and outside the train complies with the standards and, if not, take the proper countermeasures in order to bring the values below the limits.

The instruments that the EMC engineer has in his hands are the EMC theory and the experience gained in the previous projects. It is therefore clear the importance of the simulation, performed to estimate the field values generated by the on-board power equipment and the amount of field transmitted inside the train. One of the most important elements necessary to properly perform those estimations is the calculation of the carbody shielding effect by knowing the carbody design and material.

The first part of this article will be focused on these aspects of the EMC design.

In order to prove that the values generated by the model are correct, the second step is to measure the shielding effectiveness on a real carbody, as soon as it is available. The second part of this article will be focused on the measurements done by Bombardier Transportation in a carbody of a distributed power train.

II. CARBODY DESIGN AND MATERIALS

The train carbody floor frame, object of this study, is made of two horizontal aluminium sheets with a thickness of 3.8 mm located at a distance of approximately 60 mm from each other, the two sheets are separated by aluminium stiffening ribs placed with an angle of 45° from the horizontal plane; this structure is obtained with a die casting process.

The total thickness of the carbody floor is 65 mm.

A cross section of the carbody floor frame is provided in the following Fig 1.

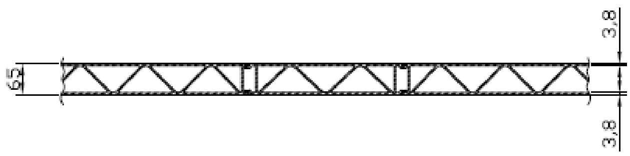

Fig 1 - Carbody floor - Section view

In the train the cables and the power equipment (i.e. traction inverters, transformers, etc.) are located just under the carbody floor; the power cables are installed inside a rack directly screwed on the carbody underframe, the power equipment is mounted below the rack.

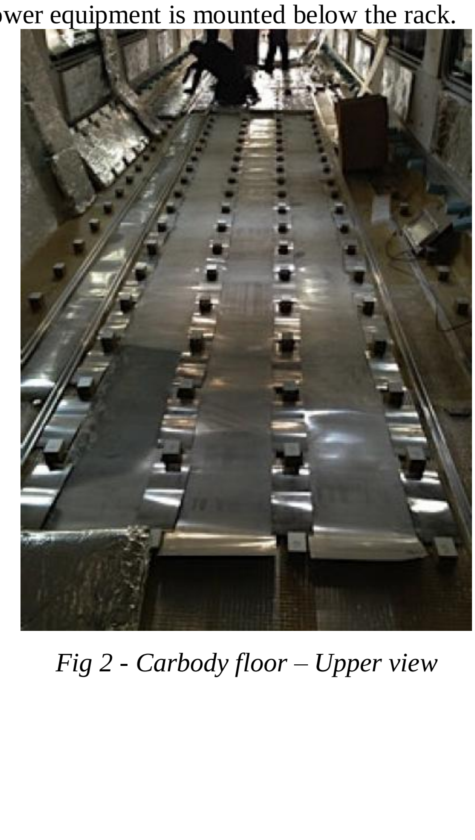

Fig 2 - Carbody floor – Upper view

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The carbody shielding effectiveness measurements were done on a train carbody in the factory during the assembly phases of the train; since the train was still in construction, the carbody did not contain any other equipment (i.e. cables, bogies, power equipment, etc.); this allowed us to perform the measurements without the influence of other ferromagnetic materials.
Assuming that the major source of magnetic field is the cable rack, the measurements were aimed to simulate the field generated by the cables by placing the field generator just under the floor.

III. THEORY AND SIMULATION

The theory of the magnetic field shielding effectiveness of a sheet of metallic material is well known. A short summary of this theory is presented in the following paragraphs (Ref. [5]).
The magnetic field Shielding Effectiveness (SE, in % or in dB) of a metallic material is mainly due to three principal effects:

1. Electromagnetic reflection (R);
2. Electromagnetic absorption (A);
3. Multiple reflections of the electromagnetic field inside the metallic material.

An explanation of each effect is given below.
-Electromagnetic Reflection. The incident magnetic field can be reflected by the surface of the metallic material, the amount of reflected field is dependent by the distance from the source and the angle between the source and the reflective surface; also the frequency of the EM field affect this phenomena.
-Electromagnetic Absorption. This phenomenon is due to the generation of Foucault currents inside the material induced by the magnetic field.
The absorption of an EM field inside a metallic (conductive) material is function of the following parameters:

- Electrical conductivity (σ [Ω^{-1}]) of the material - Measures the material's ability to conduct an electric current.
- Magnetic permeability (μ [Hm^{-1}]) of the material - Measures the ability of a metallic material to conduct the magnetic flux; a high permeability gives better magnetic field conduction. The magnetic permeability is the product of two terms: the permeability of vacuum ($\mu 0 = 4\pi \times 10^{-7}$ Hm^{-1}) and the relative permeability of the material (μr). Ferromagnetic materials (like iron or carbon steel) are very suitable for this shielding purpose at low frequencies, because μr is very high ($\mu r \approx 180$) for frequencies below 1 kHz. At higher frequencies (greater than 1 kHz) the relative permeability is more or less equal at the one of the air ($\mu r = 1$). For this reason, at high frequencies, the magnetic field shielding effectiveness of a ferromagnetic material decreases.
- Thickness (d [m]) of the material
- EM field penetration depth (δ [m]) - is a measure of how deep an electromagnetic radiation can penetrate inside a material. It is defined as the depth at which the intensity of the EM field inside the material falls to 1/e (about 37%) of its original value at the surface. The penetration depth δ can be calculated with the following equation (1):

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (1)$$

Observing the equation, the penetration depth is frequency dependent (the higher the frequency the lower the penetration depth). Therefore if the permeability of the material is low (like aluminium or copper) at higher frequencies the shielding effectiveness grows rapidly due to this phenomena.
The shielding effectiveness is also depending on the thickness of the material:

- Minimum shielding (95%, SE = 30 dB) requires a thickness of at least 3δ.
- Medium shielding (99%, SE = 40 dB) requires a thickness of 5δ.
- Excellent shielding (99.999%, SE = 120 dB) requires a thickness of at least 11δ.

At DC or low frequency the bulk specific conductivity is important for electric shielding.
At higher frequencies the currents in the conductors are concentrated into the surface and the surface conductivity becomes more important than the bulk conductivity. This surface concentration of current increases with frequency, conductivity or permeability (see equation (1) for penetration depth).
Since at higher frequencies good surface conductivity is required, conductive coatings and cladded layers are used.
Al and Cu (reference) have a high conductivity: Al = 37.3 $\Omega^{-1}m^{-1}$, Cu = 59.5 $\Omega^{-1}m^{-1}$, but a low relative permeability: $\mu r = 1$. They are good for electric field shielding, but bad for magnetic shielding.
-Multiple Reflections. If the shield is composed by many layers separated by other materials (like air) there is the phenomenon of multiple reflections of the EM field. This is the case of a train carbody that it is composed by two sheets of metallic material separate by metallic ribs. In this case the shielding effectiveness is increased.

Any slots, holes or imperfection on the frame compromising the shielding integrity assumed so far can reduce the shielding effectiveness. During the measurements of the attenuation, it was observed that inspection holes and other reductions of floor frame thickness are present: it is expected that, if cables are located nearby, the induction magnetic field may be much

higher, since the assumed attenuation is drastically reduced.
For this reason it is highly recommended that: cables are routed away from these apertures; if not possible (since these holes and apertures are there to ensure the access to the same cables), additional shielding must be installed on the power cables, on the doors of inspection holes, cabinets access and on cable duct sides, where the magnetic field can flow around the floor frame.

IV. ESTIMATION OF THE SHIELDING EFFECTIVENESS (SE) OF THE CARBODY

The carbody structure is explained in Section II.
All the power cables of the train will be placed inside an underframe cable tray that is covered, on top and laterally, by metal planks and planes in aluminium or steel of about 2 to 3 mm of thickness.
In the presence of a sheet of metal, shielding is achieved mainly by reflection and also for magnetic field in the near field region at low frequency (our case) it is possible to identify an expression to estimate the related shielding effectiveness (SE):

$$SE\ [dB] = 14.57 + 10\ log_{10}(f d^2 \frac{\sigma_r}{\mu_r}) \qquad (2)$$

Where σ_r is the electrical conductivity of the material relative to copper, μ_r is the magnetic permeability relative to free space, *f* is the frequency in Hertz [Hz] and *d* the distance between the field source and the shield in metres [m].

The carbody structure is made of aluminium that has the following properties:

- σ_r = 0.3
- μ_r = 1, at a frequency ranging between 50 Hz and 2 kHz

The resulting SE ranges between 6.3 and 22.4 dB at 0.1 m distance and 12.4 and 28.4 dB at 0.2 m distance (6 dB more for doubled distance).

Those results are approximate since they do not take into account the shield thickness.

Tabular data obtained by testing aluminium sheets as per MIL STD 285 (Ref. [1]) confirm, for a 0.1” (2.54 mm) thickness, 8 dB @ 50 Hz and nearly 40 dB @ 2 kHz. Using iron, which has a much higher but not exactly quantified magnetic permeability, for the same thickness, SE increases to 35 dB @ 50 Hz and more than 160 dB @ 2 kHz. The distance of the source from the shield was 30 cm.

Being the floor frame a double layer of horizontal aluminium sheets of 3.8 mm thickness, located at 6 cm distance from each other, with a third equivalent sheet in between due to the internal elements (thickness of 2.8 mm), an approximate 12 dB increase of attenuation is expected.

V. FIRST BATCH OF MEASUREMENTS

The estimated value above (12 dB better than theoretical formulation in eq. (2)) is compared with the results of the measurements performed in the factory on June 28, 2012.

Measurements were performed with a source of magnetic field build with 200 turns on an open C shaped core (made of high permeability material) supplied by a signal generator.

The relative position of the source and the field meter was annotated, to be able to reproduce it in the laboratory with an equivalent magnetic field in air, without the train floor frame in between. The attenuation is found as the ratio of the two variables, the induction field without the frame and with the frame, so B_{nf} / B_f respectively.

The used field meter is an Aaronia NF5035.

The overall thickness of the train floor, after the surface treatment, was measured equal to 85 mm. The height above the floor level of the field meter suspended on its tripod was 120 mm. The distance between the C shaped core surface and the floor was 50 mm. So, the total distance between the source and the field meter was 255 mm, and that distance was used to measure the reference induction field value in free air, B_{nf}.

The results, consisting of the measured attenuation curve and the two theoretical curves (one with and one without the 12 dB additive for multiple layers) are shown in the following Fig 3.

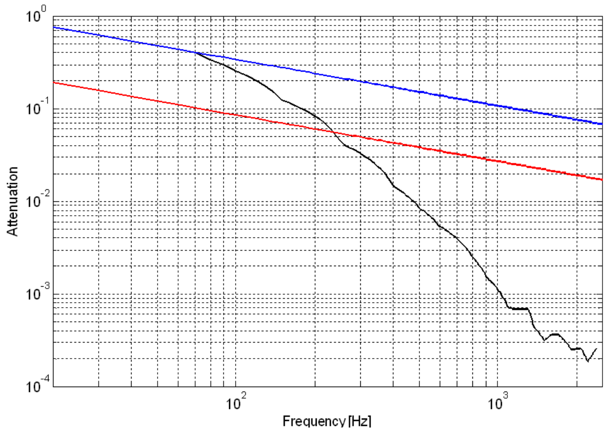

Fig 3 – Floor frame attenuation: measured (black), theoretical 1 aluminum sheet (blue), theoretical complete frame (red)

Theoretical and experimental results match quite well at low frequency, while the attenuation determined experimentally is much higher already above a few hundred Hz.
The aim of the second batch of measurements was to validate the theoretical attenuation showed in Fig 3 at low frequency by performing measurements with an higher level of magnetic field in those range of frequency.

VI. SECOND BATCH OF MEASUREMENTS

In order to verify the shielding effectiveness of the carbody floor when the magnetic field value is the same generated by the underframe cables, another batch of measurements was done. These measurements were done only at frequencies of 50 and 100 Hz, but with a higher field intensity compared to the previous batch. The aim of this was to understand if the shielding efficiency was function of the field intensity; our expectation was that the magnetic working point of the material moves and that the resulting permeability could be different.
In particular, we have measured the shielding efficiency of the carbody in three different conditions:

- Horizontal magnetic field at f = 100 Hz
- Horizontal magnetic field at f = 50 Hz
- Vertical magnetic field at f = 50 Hz

The horizontal field is a condition that better simulates the effect of the field produced by the cable located underframe.
For the test a three–axial magnetic field sensor was used, optically connected to the readout system. The measurements were done in the time domain allowing extraction of the three spatial components of Magnetic Flux Density (MFD) vector at any specific point in the measurement volume.
The winding consists of 200 coils of copper wire around a plastic frame (not ferromagnetic), connected to a power supply which injects a current value that generates a magnetic field of 2600 μT.
The field measurements were carried out after the characterization of the field generating winding. The characterization consists of the measurement of the magnetic field in air at a distance of 65 mm above the winding.
The measurement set-up is shown in the following Fig 4.

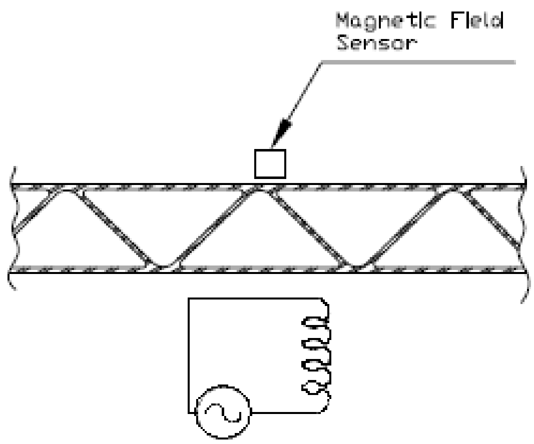

Fig 4 – Measurement set-up

The measurement results are given in the following Table 1.

Table 1. Measurement results.

Frequency [Hz]	Field reference value [μT]	Field measured above the carbody floor [μT]	Carbody damping factor
100 Hz (Vertical)	2620 μT	200 μT	13.1
50 Hz (Vertical)	2600 μT	500 μT	5.2
50 Hz (Horizontal)	800 μT	130 μT	6.2

By comparing the results of the measurements of the two batches we can notice that with higher values of magnetic field the carbody damping factor at low frequencies (under 100 Hz) is more similar to the calculated one, this proves that the magnetic working point of the carbody material moves and lead to higher permeability value.

VII. CONCLUSIONS

The result showed that the theoretical attenuation of the carbody matches quite well at low frequency with experimental results, while the attenuation determined experimentally is much higher already above a few hundred Hz: this conclusion is valid with a low level of magnetic field; on the other side, with higher magnetic field intensity, the damping factor of the carbody is quite higher, thus the final conclusion is that the shielding effectiveness of the carbody is highly depending on the field intensity generated by the source. With those results it will be possible to estimate the magnetic field intensity inside the train by optimizing the simulation model of carbody attenuation.

REFERENCES

[1] "Attenuation measurements for enclosures, electromagnetic shielding", MIL STD 285, 25 June 1956
[2] "Guide for the measurement and the evaluation of electric and magnetic fields in the frequency range 0 Hz - 10 kHz, with reference to the human exposure", Italian standard CEI 211-6, January 2001
[3] "Caratterizzazione del livello di esposizione a campi magnetici a bordo di rotabili ferroviari (5 Hz – 100 kHz), Trenitalia standard TI.UTMR.CEM001.2, May 2005
[4] "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz), ICNIRP Guidelines, April 1998
[5] JC Slater and NH Frank, "Electromagnetism", Reprint of 1947 edition, Courier Dover Publications,

1969

[6] “Norme tecniche per l’esecuzione di rilievi di induzione magnetica nel campo di frequenza 5÷500 Hz in rotabili ed impianti fissi ferroviari”, Norma sperimentale Ferrovie dello Stato – Istituto superiore di Sanità, April 9, 1999

AUTHOR’S BIOGRAPHY

Riccardo Briante was born in Savona, Italy in June 10, 1983. He received the Master’s degree cum laude in Electrical Engineering at University of Genoa (UNIGE), Genoa, Italy in September 2011. Starting from July 2011 he worked as electrical system engineer at Bombardier Transportation Italy Locomotive Division focusing on high voltage components, traction and auxiliary converters and EMC measurements. He has also collaborated with UNIGE Electrical Engineering department on EMC emission and immunity tests on automotive industry.

Pina Imbesi was born in S.Margherita L., Italy in July 11, 1975. She received her graduate in Electric Engineering in University of Genoa (UNIGE), Genoa, Italy in December 2000. Starting from 2000 she worked as electrical engineer and leading the system engineering department in Bombardier Transportation Locomotive Division focusing on power electronic as Auxiliary Converter application, Traction converter application, EMC radiated tests and counter measures application, Line Harmonic interference optimization and testing activities, Signalling systems installation and EMC related aspects, EMF emission measurement in cooperation with UNIGE Power Electronics Department.