Electromagnetic Characterization of Materials Through High Accuracy Free Space Measurements

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***Abstract*—Aerospace or automotive industries employ novel composite or 3D printed materials in their manufacturing processes to improve performance and reduce costs. Obtaining the electromagnetic (EM) characterization of these materials or a combination of them is essential to ensure safety and EM compatibility. In this paper, the development of a test bench with rod antennas for measurements in free space is presented. A complete design is described, from simulation analysis to validation measurements. The aim is to achieve robust measurements which allow the EM characterization of very diverse samples and materials, and high accuracy results that make possible to know the exact EM behaviour of these materials.**

***Index Terms*—3D printed materials, electromagnetic characterization, rod antennas, high accuracy, measurements, bench.**

I. INTRODUCTION

Over the last decade, advanced materials have earned a greater importance as design materials in many industries, mainly due to their light weight and outstanding structural performance. 3D printing and composite materials stand out among them because of their ease of design and low cost for the first ones, and the low weight while keeping a good performance for the second group. This is why they are widely used in both aerospace and automotive industries [1].

Besides, the number of electronic devices embedded in these platforms has increased too, making a critical issue their correct electromagnetic (EM) characterization, in order to ensure safety and good performance at aircraft and cars.

The crucial need for an appropriate EM characterization can be demonstrated in a couple of examples. Compared with classic metallic surfaces used in aircraft [2], carbon fiber composites present a lesser effective shielding, so studying this feature is essential to preserve the devices located inside those platforms. Apart from that, EM characteristics of 3D printed materials differ with respect to the initial raw materials, as a result of the phase change from solid to liquid state when being printed. Furthermore, the infill density in the final samples could notably modify properties such as their permitivity or loss tangent.

Therefore, it is clear the importance of the EM characterization of these new materials and the necessity of investigating modern and more flexible characterization methods. That is so because this field of research is constantly striving for better technologies and developing new structures which will have to coexist with an increasing amount of electronic devices, boosting at the same time the requirements of the measurement systems in the future.

In this paper a test bench with *polyrod* antennas for free space measurements is presented. The aim of this work is to achieve an adaptable high accuracy system to characterize a diverse amount of samples and non-liquid materials to predict their behaviour. In Section II a brief review of the characterization method used in this approach is given while in Section III the different parts of the test bench, the simulation to obtain the radiaiton pattern of the antenna and the facility design are described. In Section IV the final results are shown. Finally, in Section V the conclusions of this work are explained.

II. CHARACTERIZATION OF MATERIALS

There are several methods to electromagnetically characterize a homogeneous material, each one depending on the range of frequency, expected losses, accuracy required or the shape of the sample [3] [4].

As stated before, the test bench presented is based on free space measurements. Besides, it is a non-destructive method that does not need physical contact between the sample and the test bench itself. This system allows the analysis of not only homogeneous materials, but more complex ones, such as composite and 3D printed materials.

The Computational and Applied Electromagnetics Laboratory in the National Institute of Aerospace Technology (INTA), has a facility called BIANCA (Bistatic ANechoic CHAmber) [5] for free space measurements. It is designed to perform a broad variety of EM tests for radiation and scattering, with an estimated precision of 0.5 dB. However, the new system, while giving up some versatility, is able to detect reflection and transmission coefficient variations equal or lower than 0.05 dB.

III. HIGH ACCURACY TEST BENCH

The test bench called POLYBENCH is made up of a couple of facing *polyrod* antennas (transmitter and receiver), while the sample under test is set between them. The structure shaping the bench is rigid, ensuring that the measurement is precise, as well as covered in absorbing material, in order to decrease possible reflections coming from it (see Fig. 1).

The bench is connected to a 4 port ZVA 50 Vector Network Analyzer (VNA) designed by Rhode & Schwarz [6] through coaxial cables. A full 2-port calibration is carried out for the VNA. After the measurements, S-parameters data provided by the VNA, are exported using a software developed by the Computational and Applied Electromagnetics Laboratory.

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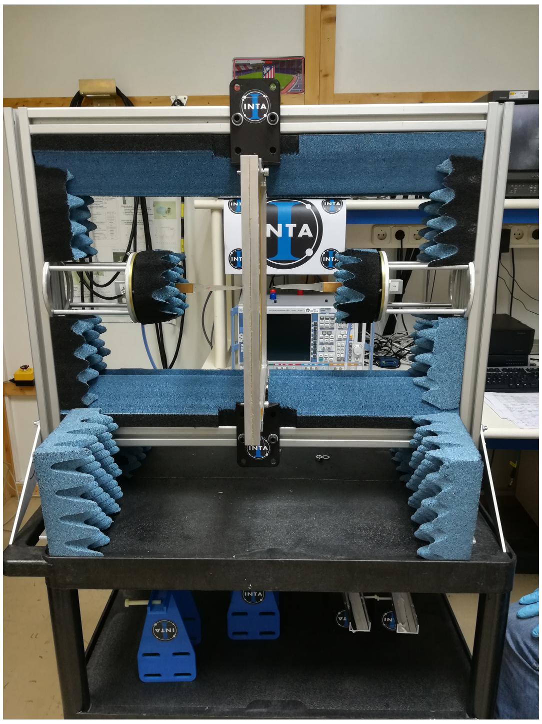

Fig. 1. Polybench

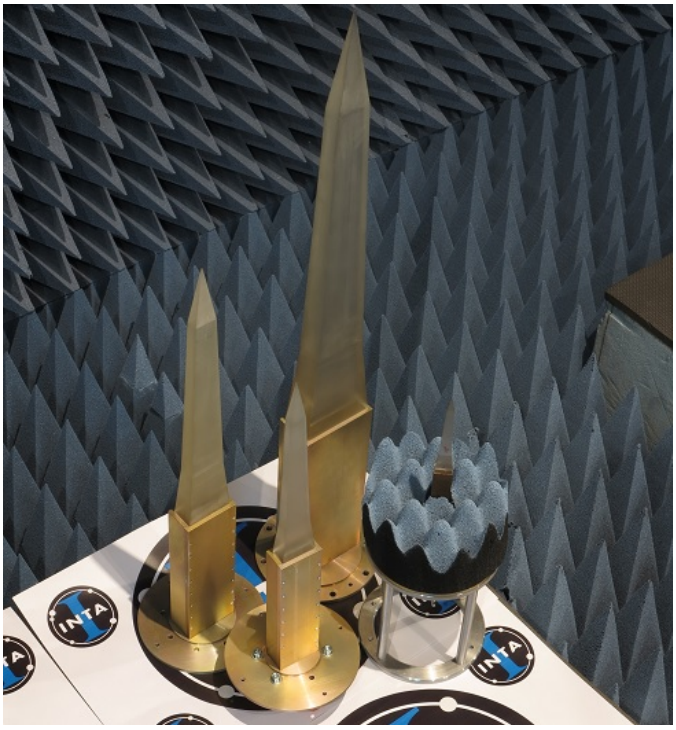

Fig. 2. *Polyrod* antennas from 2.6 GHz to 18 GHz.

A. Antenna Description

The main feature of these *polyrod* antennas is their design, capable of modifying the radiation pattern of a waveguide [7] by focusing it on the center of the sample under test. This is achieved by the pyramid-shaped dielectric placed on the waveguide, as it is shown in Fig. 2. A highly focused radiation pattern helps to reduce the difracction at the edges, providing greater accuracy during the measurement and allowing the use of smaller samples.

Rexolite [8] is chosen as the dielectric material because its dielectric constant is stable at a wide range of frequencies. The bench described in this paper is designed for WR90 and WR62 waveguides with working frequencies from 8.2 GHz to 12.4 GHz and 12.4 GHz to 18 GHz respectively. However, the bench is being improved so these working range of frequencies is widened up from 2.6 GHz to 40 GHz.

B. Simulation of Antenna Radiation Pattern

Knowing the behaviour of the electric field radiated by the *polyrod* antenna is fundamental for an optimal design of the test bench. For that reason, several simulations were carried out with the software HFSS v19.2 provided by ANSYS.Inc [9].

The model simulated is shown in Fig. 3. As a source, a 50 Ω waveguide port is used. The waveguide is modeled as a perfect conductor, while for the dielectric, the relative permittivity ($\epsilon'_r = 2.53$) and loss dielectric tangent ($tan\delta_\epsilon = 0.0006$) values from [10] are used. The truncation condition is a FEBI boundary condition (*finite-element boundary-integral*) [11].

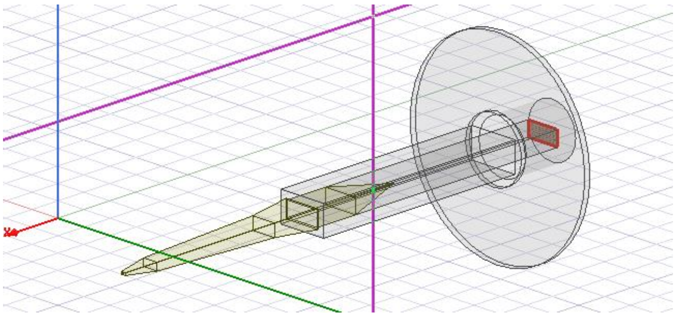

Fig. 3. Simulation of the WR90 *polyrod* antenna model.

Several perpendicular cuts to the direction of propagation of the electric field were calculated at different distances from the sharp end of the radiating element. In Fig. 4, three of these cuts can be observed at 1, 10 and 100 mm for a working frequency of 10.65 GHz in dB(V/m) units.

The radius where the electric field decreases 3 dB and 6 dB at 1 mm from the tip of the antenna is 19.30 mm and 27.95 mm respectively. At 100 mm, these values rise up to 47.77 mm and 64.48 mm. In Fig. 5 this behaviour can be observed. Displayed data are normalized with respect to the maximum field in the tip of the antenna. There are also four lines overlayed which represent the beam for -3 dB and -6 dB.

C. Facility Design

In the very first designs of these antennas, the sample under test was placed right next to the very end of the antenna [12]. However, in further studies [13] that sample was separated a

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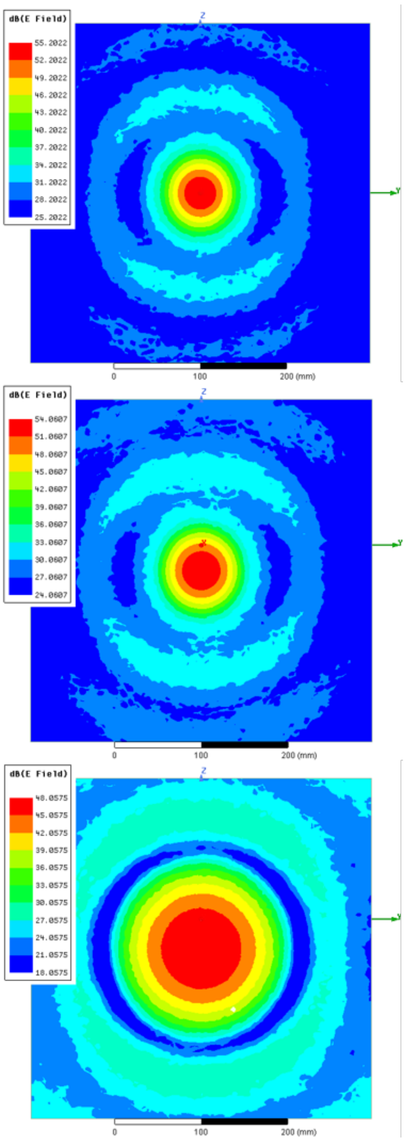

Fig. 4. Electric field at different distances from the sharp end of the WR90 *polyrod* antenna. 1, 10, 100 mm cuts respectively for a working frequency 10.65 GHz.

little distance instead, so the integrity of the material sample is maintained.

Having this into account, a final distance of 3 mm was chosen in this design to ensure both precision and safety. At that distance, the radius of decay of the signal for 3 dB is 28.74 mm, while for 6 dB is 39.46 mm.

Another key point was the positioning of the antennas and the sample. In this sense, a robust galvanized steel structure was developed, so the accurate alignment between antenna and sample is guaranteed. Also, this structure is covered by radiation-absorbent material (RAM). The aim behind the addition of the RAM material is minimizing environmental reflections. These reflections can introduce an external component to the measurement, decreasing the accuracy for the EM scattering coefficients measured.

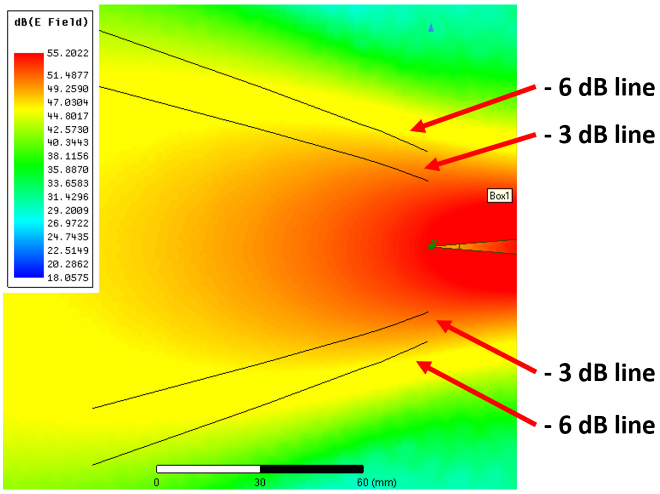

Fig. 5. Signal decay with respect to distance in the direction of the radiation propagation of the WR90 *polyrod* antenna.

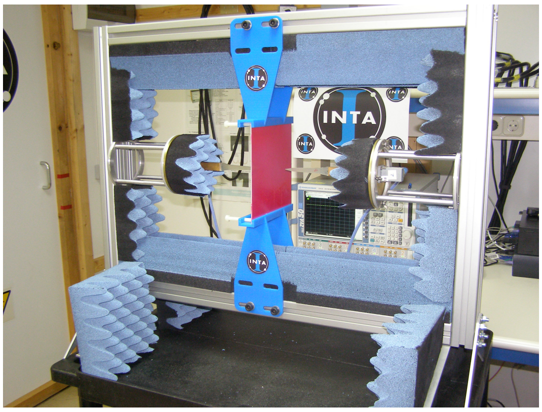

Fig. 6. Test bench with high accuracy *polyrod* antennas.

The sample holders are made of *polylactic acid* (PLA) and are interchangable. This adds some versatility to the bench, making possible to work with different sample sizes (20 x 20 cm and 48 x 48 cm) and allowing placing these samples in several positions. This enables the behavioural study in different directions for anisotropic materials. It is important to mention that these sample holders are set perperdicular with respect to the steel structure (so the piece of material in kept completely straight) and the radiation beam produced by the antennas.

In addition to all the previous features, the antennas are fixed to the structure using circular holders which, at the same time, allow an easy access to the transition connector. The final design is shown in Fig. 6.

IV. RESULTS

In this section the final results using samples manufactured from two different materials are shown: teflon® and some versions of a reflective metallic one. On the one hand, the measurements carried out using teflon® prove that the system works properly. On the other hand, the measurements carried

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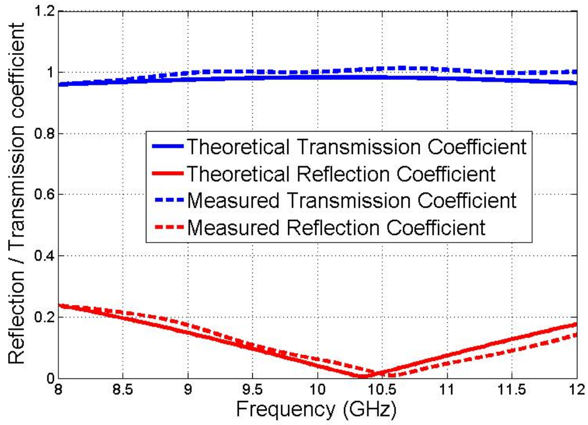

Fig. 7. Comparison of theoretical and measured reflection and transmission coefficients of teflon®.

out over the metallic samples, help to estimate the accuracy of the method.

A. *Reflection and Transmission Coefficient of teflon®*

The reason behind choosing teflon® as the material to verify our system is that it has been already charaterized previously in several studies, so it has a well-known permitivity. As an example, according to [10], teflon® has a stable $\epsilon_r' = 2.1$ and $tan\delta_\epsilon = 0.001$ in a wide range of frequencies.

Taking these dielectric constants as a starting point, theoretical reflection and transmission coefficients are calculated [14]. These will be used to validate the test bench.

WR90 waveguide antennas were used to carry out the teflon® measurements in our bench, for a frequency range from 8 to 12 GHz.

It can be observed in Fig. 7 that exists a great similarity between the theoretical and the experimental results, proving that the bench is working properly. From transmission and reflection coefficients, the permitivity and the loss tangent of a material can be obtained [15].

B. *Measurements with several versions of the metallic sample*

The material chosen to check the accuracy of the measurements is a reflective metallic material used for the manufacture of calibration targets for satellite synthetic aperture radar (SAR) systems, which must have a highly controlled level of optical reflectivity. For this experiment, it was necessary to reduce the mirror effect of the material. Different finishes of the original sample were measured, in order to evaluate the losses in terms of radiofrequency reflectivity.

In Fig. 8 the different versions of the metallic material are shown. The first version is achieved by applying a light polish on the surface, which leads to certain heterogeneities on it. The second version consists of an intense polish that leaves a more homogeneous surface. The third version is achieved by applying a paint coating.

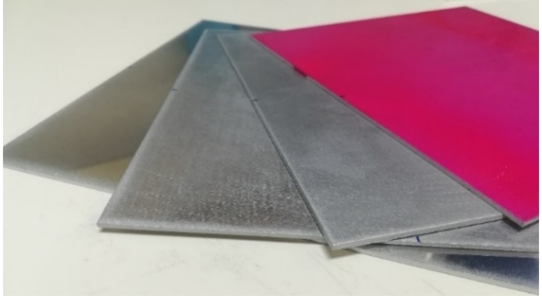

Fig. 8. Original sample and the different versions of the SAR material.

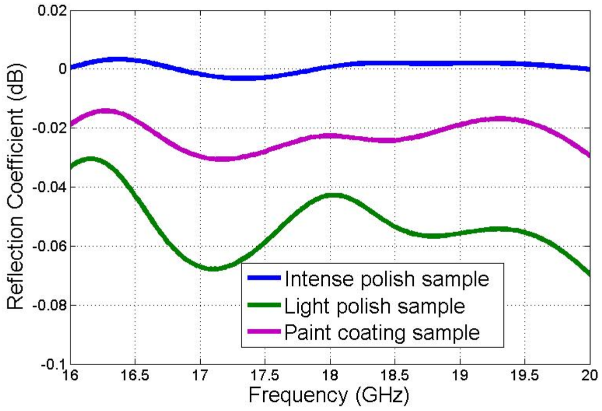

Fig. 9. Reflection losses (dB) over the SAR samples.

The results depicted in Fig. 9 are the reflection coefficients of the three different versions of the material used to calibrate SAR systems, taking as a reference the original non polished sample. All of them were measured with the WR62 *polyrod* antennas . A working frequency of 18 GHz and a bandwidth of 4 GHz was set.

Analyzing Fig. 9, it is clear that the variation in terms of reflectivity with respect to the original sample is merely undetectable for any kind of measurement system with a standard accuracy. The difference in the reflection coefficient of the sample with the intense polish with respect to the original is due to the measurement error of the test bench itself. In the sample presenting the paint coating, the absorption of that extra layer produces a reflection coefficient slightly lower than the intense polish sample (0.02 dB approximately). Finally, the sample where the light polish was applied shows the highest reduction on its reflection coefficient with respect to the original sample (about 0.06 dB less).

V. CONCLUSION

Designing new outperforming materials and the spread of their use in aerospacial and automotive industries, besides the increase of the embedded electronic systems, makes the development of modern EM characterization systems essential. They need to be more accurate and adaptive than ever.

This paper presents the design of one of these new systems, a test bench based on free space measurements formed by *polyrod* antennas, called POLYBENCH.

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The study of the EM field generated by the radiation system allowed the optimization of the sample position under test, according to accuracy and safety criteria.

The robust and stable structure makes possible a correct alignment between antennas and sample. Furthermore, the sample holder added to the ability to change the antennas facilitate to work with different sizes and geometries of samples for a broad range of frequencies, increasing the measurement ability of the system.

Measurements carried out using teflon® have been used to validate the new facility and measurements over a range of metallic plates with different finishes have been used to verify the accuracy of the test bench, which is proved to be able to detect variations in the reflection coefficient under 0.05 dB.

For further research it is planned to upgrade the POLY-BENCH frequency range from 2.6 GHz to 40 GHz and a specific error budget is being developed for the whole measurement system.

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