Characterization of Time Domain EM Field Double-loaded Curved Loop Probe

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***Abstract*— in this paper, we present and analyze the performance of a double-loaded curved loop probe to measure simultaneously electric and magnetic fields (EMF). The aim is to construct a probe that can be fitted to non-planar structures and have a proper response to EMF. The curved probe is studied in comparison with well-known planar probes, which have been verified and used previously. The time-domain data obtained through EM simulation allow us to identify if the probe's response is suitable although its geometry. Finally, the probe has been constructed and evaluated with experimental test, measuring and validating the conclusions find out by the EM simulation.**

Keywords*— *Time-domain measurements, Electromagnetic interferences, double-loaded loop probe, FDTD, EM simulation

I. INTRODUCTION

In the field of Electromagnetic Compatibility (EMC), Electromagnetic Field (EMF) probes are necessary to measure interference. Industries like the aeronautics, healthcare, railway or automotive need these probes to quantify the incident EMF at their equipment [1],[2],[3]. However, the placement of EMF probes usually produces distortion of the fields and other times it is not possible to allocate them. Moreover, the EMF probes available at the market are broadband probes, which integrate the response of the full bandwidth in a single value. Hence, there is no way to decompose the measured signal at the frequency domain, being not possible to measure separately a single or various frequency bands, which is necessary to evaluate interference to the communication systems. To overcome this limitation and accomplish with the objective, time-domain based probes are developed. In previous publications [4], laser probes are directly connected to oscilloscopes in order to obtain the EMF. Making possible to find out the electric field (E-Field) and the magnetic field (H-Field) at the same time that the time-domain data is stored. Therefore, these broadband EMF probes in combination with post-processing allow us to split interferences and analyze separately any desired frequency band.

In this paper, these time-domain based probes will be used and modified with the idea of attaching them to structures. Currently, the possibility that novel materials and technologies like the 3D printing offers us novel approaches to construct EMF probes fitting the shape with a non-invasive probe. As an example, the aeronautic industry is interested in developed probes that can be fitted to composite fuselage structures instead of placing them in the middle of the bay. For this reason, we will study if it is suitable to curve the probe and still have a device, which is capable of measuring simultaneously the electric and the magnetic field in a traceable and confident way. Even more, with this approach of constructing sensors within the structure, we can dismiss the magnitude of the E-Field or the H-Field and focus on the voltages and currents coupled at a certain structure when we are interested in comparative results. The same approach is done in EM simulation when currents and voltages are computed at cables, or other equipment parts.

Therefore, we are developing a curved double-loaded loop probe to compute the E-Field and the H-Field, characterizing its performance through EM simulation and experimental measurements. In section II, the double-loaded curved loop is described. In section III, EM simulation is employed to view if an excessive curvature of the loop produces an undesired performance of the probe, measuring high field components where no probes' response Is expected. Finally, in section IV, the curved probe presented in section II is evaluated within EUROTEM®2 cell to corroborate the conclusions obtained at the simulation stage.

II. DOUBLE-LOADED CURVED LOOP PROBE

A. *Planar double-loaded loop probe*

The reference EMF double-loaded loop probe has a planar shape validated in previous works [4]. In fact, E-Field was measured with this probe within the cavity of an Unmanned Aerial Vehicle (UAV) fuselage, comparing its successful results with other commercial probes (Fig. 1).

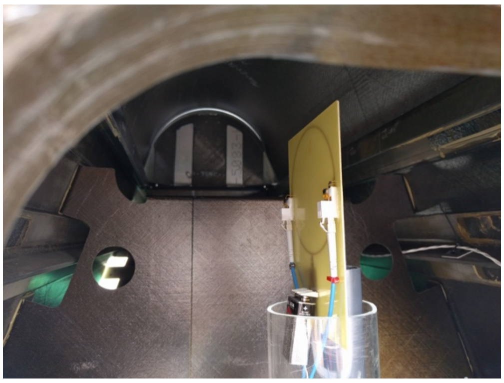

Fig. 1. Planar double-loop probe employed to measure the EMF within the fuselage of an unmanned air vehicle.

A double-loaded loop probe is a loop with two gaps at opposite sides loaded with identical loads. The probe was presented by King in 1969 [9] and later developments of Kanda and Wieckowski in 1980s [10], [11]. The presence of an electromagnetic field induces a current within the loop, which is the contribution of the E-Field and the H-Field. Meaning that the response of the probe is equivalent to the superposition of an electric dipole and a magnetic loop. The addition of the signal is directly related with H-Field and the

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subtraction is associated with E-Field. In previous developments [12-14], the addition and subtraction were carried out at the electronics attached to the Printed Circuit Board (PCB) probe. On the other hand, the probe shown in Fig. 1, improved previous works by reducing the electronics transforming the current directly to light with the lasers. In this design, an oscilloscope acquires the time domain data with two channels and all the post-processing stage is done with a personal computer (PC). Having the advantages of reducing the electronics at the probe and the parasitic effects, or to acquire the time-domain signal. This data increases the post-processing possibilities like carrying out FFT operations allowing us to analyze for example the EMF at the any desired frequency band or compute statistical detectors like Amplitude Probability Distribution (APD) [5].

B. Curved Probe

As mentioned before, we want to study the performance of double-loaded probes when there are used in non-planar structures. The constructed probe is a curled one to study the effect of attaching it to a curved structure, as it could be the fuselage of a UAV. As it is shown in Fig. 2, a 10 cm loop diameter probe is over a flexible substrate enabling to follow a cylinder structure that resembles the curved UAV fuselage. The lasers responsible to convert the Radio Frequency (RF) current to light and serve as the loop loads are located over a small printed circuit board (PCB). Finally, to power up the lasers, a 9 V battery is placed to generate a constant current source employing an LM117 voltage regulator.

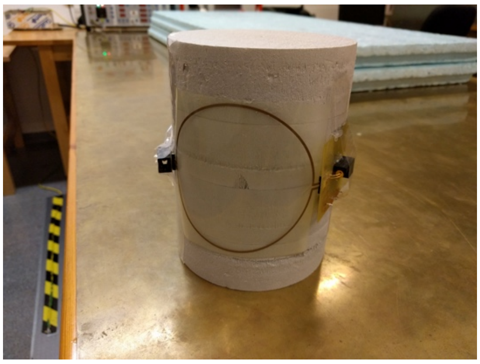


Fig. 2. Developed double-loop curved probe employed to measure simultaneous the E-Field and the H-Field

III. EM SIMULATION

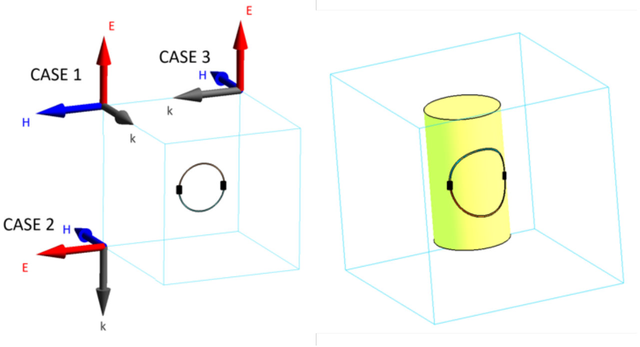
The aim of employing EM simulation is to characterize the performance of the curved EMF probe in comparison with the reference planar one. The EM simulation permits to conduct ideal plane-wave excitation and discard parasitic contributions from the electronics or the battery, focusing only on the geometry of the probe.

A. EM modeling

To carry out the EM simulation, we select the Finite-Difference Time-Domain (FDTD) method, which is highly used for EMC EM simulations [2],[6],[7]. FDTD method is based on computing in different time-steps the EMF on a space discretization, evaluating all frequency spectrum with a single simulation. This is the main advantage for us, as we want to evaluate the frequency range from 100 MHz to 1 GHz and the probe described in section II works with time domain instrumentation.

Regarding the EM model, we define two different geometries to simulate (the reference planar probe and the curved one). The loop is composed of two semicircles with a 5 cm radius and the material is Perfect Electric Conductor (PEC). At the extremes of the semicircles, there is a gap of 1 mm, which is filled with 50 Ohm loads. The planar double-loaded loop probe in the middle of the simulation space (Fig. 3a) and the curved one is fitting the shape of a 6.36 cm radius cylinder (Fig. 3b). Considering the simulation source, we define three different orientations for the plane-wave excitation:

- Case 1 (E-Field max, H-Field min): the first simulation produces a maximum E-Field and a minimum magnetic one response for the orientation of the probe;
- Case2 (E-Field min, H-Field max): in the second case we have a maximum response to the H-Field and a minimum for the E-Field;
- Case 3 (E-Field max, H-Field max): finally, in the third case we maximize both, the E-Field and H-Field response.



a) *b)*

Fig. 3. EM model view for the planar probe a) and the curved probe b)

The aim of the three simulations is to analyze if the curvature of the EMF probe produces unwanted phenomena. We should ensure that when the probe is set up to measure a maximum E-Field, non-contribution of the H-Field is obtained and vice versa. The input signal for the three different polarized plane waves is a multitone signal. This signal, synthesized previously in MATLAB®, is composed of tones from 100 MHz up to 1 GHz with a 1 MHz step. Consequently, in each FDTD simulation, we have 901 tones exciting simultaneously the probe. The results will be analyzed at these frequency bins, which will be comparable with the experiment conducted in section IV.

The simulation is performed using Sim4Life v3.4 software from Zurich MedTech AG (ZMT) [14], with a space discretization of with 4.8 MCell. The simulation is computed by an Intel® Core™ i7-7700 CPU @ 3.6 GHz with 16 GB (RAM) machine. Therefore, six different simulations are carried out, with three different plane-wave polarizations for the planar and the curved probes.

B. EM simulation results

The E-Field and the H-Field are computed according to the double-loaded loop definition. Adding or subtracting the time-domain signals at loads of the probes and afterward computing the Fast Fourier Transform (FFT) with

MATLAB®. However, firstly as a quick way to evaluate the possible distortion of the measured fields caused by the curvature of the loop, we check the directivity of the measuring probe, thanks to the post-processing tools provided by the Sim4Life simulation platform. In Fig. 4a), we observe the directivity diagram for the planar probe when the plane wave is polarized to receive the maximum E-Field and the minimum H-Field. On the other hand, in Fig. 4b), the directivity results for the curved probe are displayed.

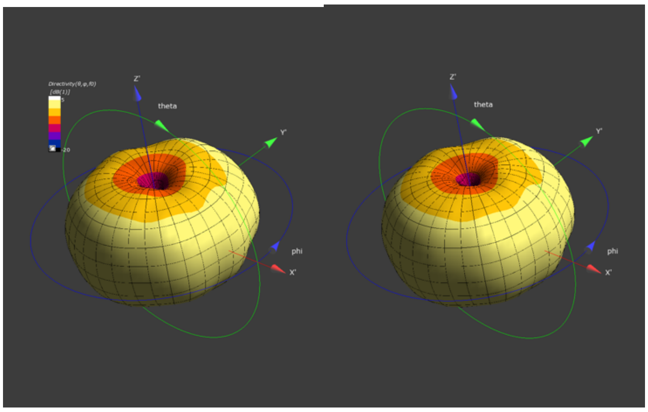


Fig. 4. Directivity for the planar probe a) and the curved probe b) when the plane wave is polarized to receive the maximum E-Field and the minimum H-Field.

If we compare the directivity diagrams, we rapidly conclude that the curvature of the probe does not seem to produce a meaningful distortion on the reception of the EMF. Despite the loop has been curved with the cylinder shape, the directivity pattern still corresponds to a dipole and only very slight differences are observed. With the results of the directivity, we can be quite confident about the performance of the probe. However, an extensive analysis should be done to quantify the differences between the planar and the curved probes.

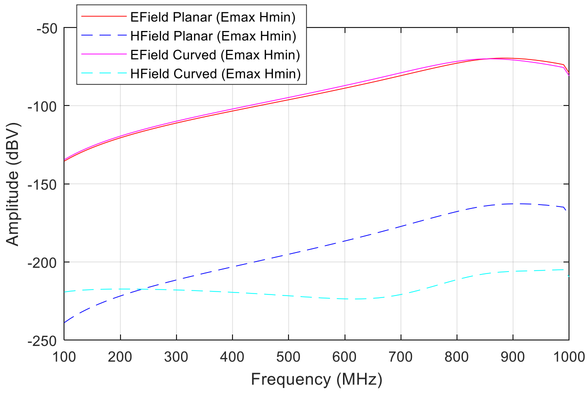


Fig. 5. E-field and H-Field response for the planar and the curved probes when we excite the simulation for an E-Field maximum response and H-Field minimum response (case 1)

The first results displayed, are according to the planar and curved probes for case 1, when the polarization of the plane wave produced a maximum of the E-Field and a minimum of the H-Field (Fig. 5). Otherwise, in Fig. 6, the results are for case 2, when the plane-wave produces a maximum H-Field response and a minimum E-Field. It is important to highlight that the response of the probes matches in terms of shape and amplitude for the dominant E-Field or H-Field. Then, we can ensure that we have almost the same performance when the planar or the curved probes are used to measure case 1 or case 2.

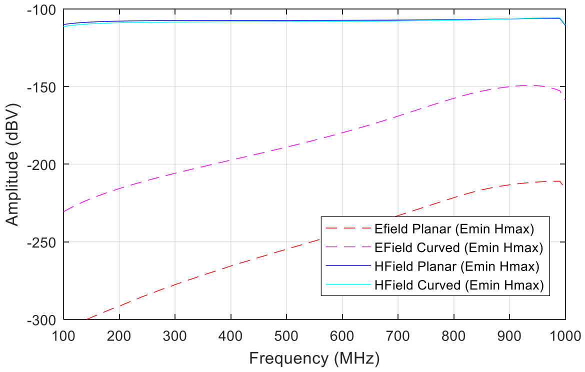


Fig. 6. E-field and H-Field response for the planar and the curved probes when we excite the simulation for a H-Field maximum response and E-Field minimum response (case 2).

Otherwise, we have to study the residual measurement of the non-dominant field. As it has been mentioned before, the curvature of the probe can induce some errors raising the level of the field orthogonal. When we obtain the E-Field with the curved probe, the H-Field results increases between 60-70 dB compared with the planar probe response. Therefore, it is clearly observed that the curvature has an impact on the residual field. However, the margin between the dominant-field and the residual is still huge, having a margin between 80-100 dB. Complementary, if we evaluate the H-Field performance, it is similar as we have a great margin between the maximum and minimum response (70-120 dB). In this case, it is not so clear that the curvature makes to receive more level of H-Field, depending on the frequency range, the planar loop receives more H-Field for minimum response case. In conclusion, after simulating case 1 and case 2, we can use the curved loop as the planar when maximum conditions E-Field or H-Field are considered. The results show us that there is not a significant variation (less than 2 dB) when the dominant field is measured and the margin to the residual E-Field or H-Field is still higher than 70 dB.

The next case to calculate is case 3, where the orientation of the probes contributes to a maximum response for the E-Field and to the H-Field. The results obtained for the planar and the curved EMF probes are displayed in Fig. 7. In this case, we also obtain similar results when we compare the planar and the curved probe. The shape and the amplitude match between them with differences up to 3 dB offering us a similar performance. Alternatively, if we compare the results between case 3, and case 1 or case 2, important differences appear even when using the planar or the curved probe (Fig. 7). In case 3, we should have the same response for the maximum component but we see a reduction of the sensibility of the probes compared with the single-field maximum response. To highlight this difference, we have computed the reduction of the field in Fig. 8.

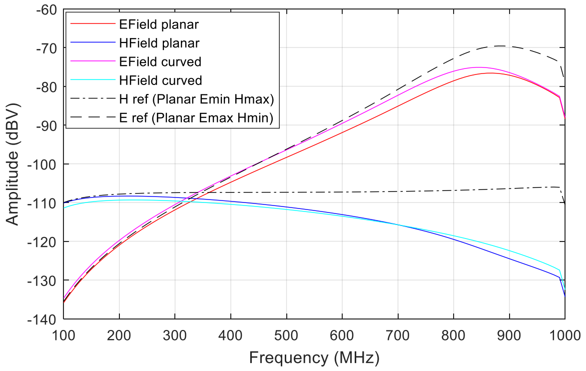


Fig. 7. E-field and H-Field response for the planar and the curved probes when we excite the simulation for an E-Field and H-Field maximum response (case 3).

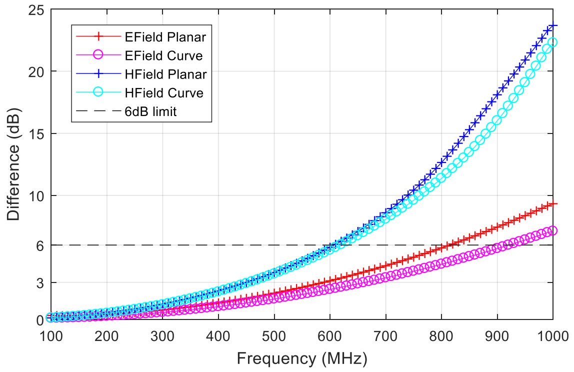


Fig. 8. The difference when probes are placed to receive the maximum E and H fields

The reduction of the level measured is present for the planar and the curved probes and it is intrinsic to the double loaded loop. This effect is related to the size compared to the wavelength that we want to measure. As the size of the loop is not small compared to the wavelength, the theory of the double loop probe is compromised. In Fig. 8, it is clearly observed that the difference is increasing with the frequency range. Therefore, the useful bandwidth of the double-loaded loop probe is limited. If we limit the bandwidth of the probe to have a difference lower than 6 dB between different probe polarizations, we reach a bandwidth of 600 MHz for the H-Field and 800 MHz or 900 MHz for the E-Field.

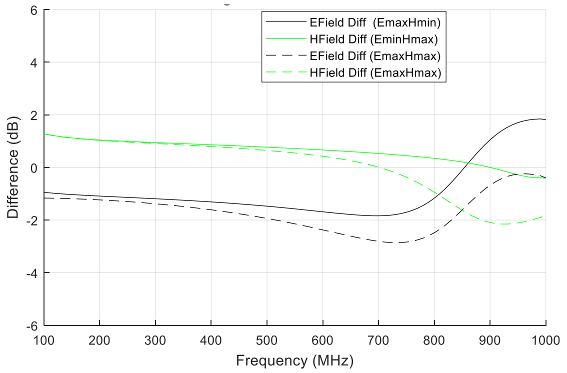


Fig. 9. Amplitude differences between the planar and the curved EMF probes.

The conclusion from all the EM simulations is that we have minimum differences between the planar and the curved EMF probes. In Fig. 9, differences are quantified for all the simulated cases. Instead, we have seen that the curved probe does not introduce significant contribution to the orthogonal field response. Finally, we have seen that the bandwidth of the probe is limited by the polarization of the probe but is the same for planar or curved configuration.

IV. EXPERIMENTAL RESULTS

The probe described in section II is employed to verify experimentally the performance of the curved probe found in the EM simulation section. The experiment is conducted inside EUROTEM®2 cell emulating plane wave conditions [16]. However, the propagation within the cell is not as ideal as in the EM simulation software and the fields are not pure orthogonal [16]. Moreover, as we only have available a reference E-Field probe to calibrate the field we focus our experimental study in EM simulation case 1, where the probe's response to the electric field is maximum and the magnetic is minimum. In this way, according to the simulation, this test should be sufficient to demonstrate the viability of using curved probes instead of the planar ones. Parasitic effects are present at the test due to the probe construction as the 9 V battery, the short PCB tracks, the uncertainty of the probe's placement or the non-perfect orthogonal plane-wave generation.

Regarding the measurement set-up, the reference probe selected is an Amplifier Research (AR) probe model FL7006 capable of measuring the three-axis E-Field with an accuracy of 0.8dB between 100 MHz and 1 GHz. With this AR reference probe, a target field of 5 V/m between 100 MHz and 1 GHz stepped 10 MHz is generated by the EUROTEM®2 cell. The input signal is generated by a Hameg HM8134 RF generator, which is amplified by an IFI B1080M-10 RF amplifier.

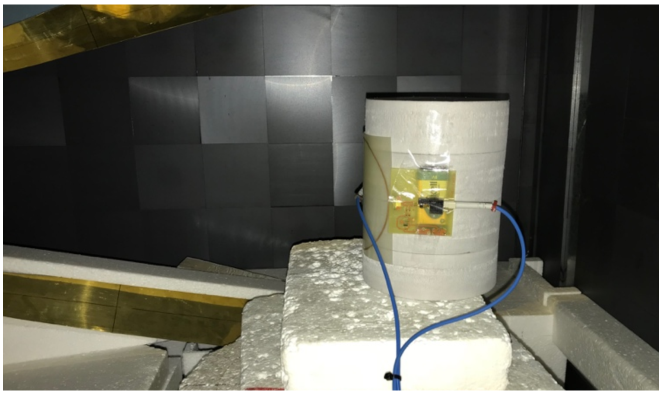


Fig. 10. The curved probe placed within the EUROTEM®2 cell

After the calibration is carried out with the AR reference probe, the planar probe and the curved probe are placed inside the cell (Fig. 10). The lasers are connected via FO link to two channels of a Tektronix DPO5104B oscilloscope, in which the time-domain signal is acquired. It is necessary to mention that it is mandatory to have multiple channel synchronous input at the receiver. Afterward, a PC running Matlab software obtains the response to the E-Field and the H-Field (Fig. 11). Regarding the response to the E-Field, the planar and the curved probes show the same response in terms of shape and a slight difference up to 3.5 dB in the amplitude. On the other hand, the H-Field is negligible compared with the E-field as it should be a minimum response to case 1. However, due to the non-perfect plane wave or the parasitic effects of the probe we have a higher contribution compared with the EM simulation. The results from the EM simulation show a difference close to 70 dB (Fig. 5) and, in the experimental test, we have a margin of 15 dB.

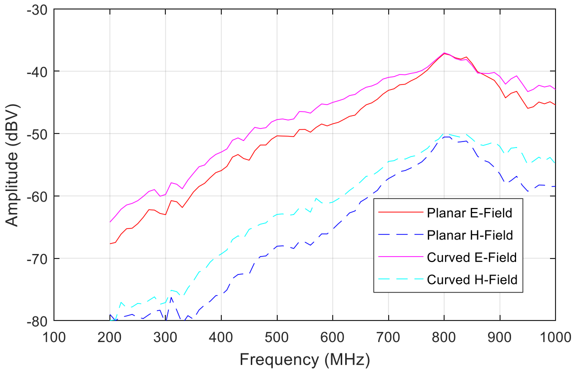


Fig. 11. E-field and H-Field response for the planar and the curved probes when we perform the experimental measurement for an E-Field maximum response and H-Field minimum response (case 1)

V. CONCLUSIONS

Employing EM simulation tools and experimental tests, we can conclude that it is feasible to use double-loaded loop probes fitted at the shape of curved objects. E-Field and H-Field probe response is not severely compromised from remain orthogonal-field, although the curvature increases the capture of undesired field components. Despite we only conducted one experiment, EM simulation allows us to analyze effects like the probe's bandwidth when multiple incident plane waves are considered or to quantify the maximum error due to the geometry. Moreover, the limits of the probe can be reached through EM simulation removing parasitic effects. Making the EM simulation results in the boundaries to be reach by curved probes or offering measurement traceability.

Otherwise, despite the characterization has been done in the frequency domain, simulation and measurement have been obtained from time-domain data. It is important to highlight the possibilities of the TD data compared with the single-value available with market probes. TD data offers us the possibility to compute any desired output-value at certain frequency bands or use statistical detectors through post-processing. Moreover, obtaining directly the voltages or currents that are coupled to the probe, instead of the incident E-Field and H-Field, can be very useful to validate EM numerical simulations of complex structures like Unmanned Aerial Vehicles.

ACKNOWLEDGMENT

This work was supported in part by the EURAMET 15RPT01 research project (the EMPIR is jointly funded by the EMPIR participating countries within EURAMET and the European Union), by the Spanish "Ministerio de Economía, Industria y Competitividad," under project TEC2016-79214-C3-2-R (AEI/FEDER, UE), by the "Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement de la Generalitat de Catalunya" and the European Social Fund and The author(s) would like to acknowledge the contribution of the COST Action IC1407 'ACCREDIT'.

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