Leveraging Near-Field Measurement Data to Enhance Digital Twin Accuracy

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***Abstract*— This paper addresses the challenges of achieving high-fidelity digital twin models for electrically large structures, particularly in areas such as electromagnetic field scattering, antenna placement, electromagnetic compatibility, and coupling evaluations. The "Link" approach combines spherical near-field electromagnetic measurements with advanced post-processing techniques to produce a highly accurate digital twin of the radiating element. This digital twin can then be exported to any full-wave electromagnetic solver and integrated into large structures, such as the aircraft studied in this work. In this paper, we investigate and validate the accuracy of this approach by comparing the digital twin model derived from measurements to a full-wave simulation of the same antenna element using the Ansys HFSS solver. The radiation patterns, with the antenna placed in various positions on the electrically large aircraft, closely matched, confirming the effectiveness of the "Link" approach.**

***Index Terms*— Near-field antenna meausrements, Digital twin, Electromagnetic full wave simluation, radiation pattern, large strucutre simulation.**

I. Introduction

Modern transportation systems integrate a large number of wireless communication protocols and thus a large number of antennas. For example for an airbus 320 aircraft integrates about 35 antennas [1] working at different frequencies, using different protocols, such as GPS, Altimeter, VHF, Radar, etc. The same is true for modern vehicles, drones, and ships, integrating a large number of wireless communication modules. The modern transportation system integrators face an uphill task to ensure that all these different communication antennas will work efficiently and reliably when they are used in the real world. When starting a new aircraft design, the integrator faces the challenge to select the best antenna module, and place it at the optimal location on the aircraft, to ensure optimal performance in terms of quality of service. The quality of services is mainly driven by losses and antenna radiation pattern. In addition, the electromagnetic compatibility (EMC) issues have to be addressed early on in the design phase to minimize the interference (or coupling) between different radiating elements, once they are integrated on the aircraft.

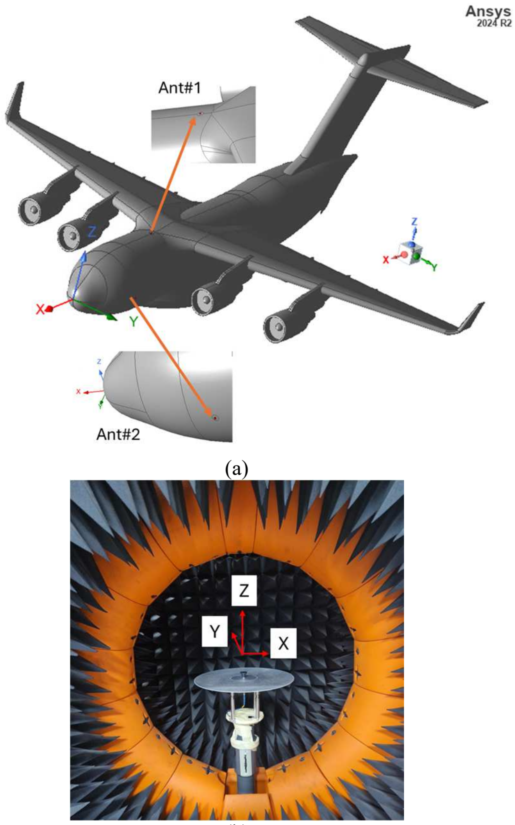
With the advancement of numerical simulation tools and high power computation equipment, it has become possible to simulate very large structures (in terms of physical size and electromagnetic wavelength size). But when making a digital twin of a complex antenna (such as a multi-element phased array) typically used in modern aircrafts, there are several challenges. The accuracy to characterize the different materials that constitute the antenna such as, the substrate permittivity, substrate thickness, packaging, radome thickness & reflectivity, printed circuit boards (PCB) metal thickness, etc., becomes critical as we go higher in frequency. The variation of slight material changes (e.g. thickness / roughness of metal on PCB, thickness / roughness of radomes, and permittivity dispersion over the substrate area) can have a significant impact on the antenna performance. Even on the same antenna with large number of elements, the variation can be challenging to model accurately in digital twins.

To address such issues, the use of near-field sources from measurement data have emerged as the go to solution since few years. The main idea is to combine the near-field electromagnetic field measurements and advanced post-processing techniques to produce a realistic digital-twin, or near-field source [2]. This approach has been validated in recent works for diagnostics [3], antennas placement [4], and coupling evaluation [5].

In this paper, the antenna placement and impact of radiation pattern of an antenna when it is placed on a curved surface on a large aircraft structure is studied. The paper is organized as follows. Section II includes the description of the problem with the reference scenario and proposed approach to evaluate the radiation pattern. The results are presented in section III and conclusions are drawn in section IV.

II. Description of Scenario

For this study, the C17 aircraft model is selected [6]. It has a very large structure in terms of physical dimensions (50.3 m in length and fuselage diameter of about 6.86m). A small monocone antenna (MVG SMC2200) working at 3 GHz [7] was selected for antenna placement at different locations on this aircraft model. In terms of wavelength the aircraft size is about $500\lambda_0$ in length and $68\lambda_0$ in fuselage diameter at 3 GHz. The reference setup consists of the full-wave model of the SMC2200 antenna placed at two locations on the aircraft as shown in Fig. 1(a). Ant#1 is placed on the top position of the fuselage and Ant#2 is placed on the more curved surface, on the side of the fuselage. The Aircraft model was provided by Ansys France for this study, and all the simulations are done in the Ansys-HFSS simulation tool [8]. The full-wave antenna model was shared by MVG, using the encrypted format available in HFSS. The encryption of the antenna model protects the IP of the antenna manufacturer.



(a)

(b)

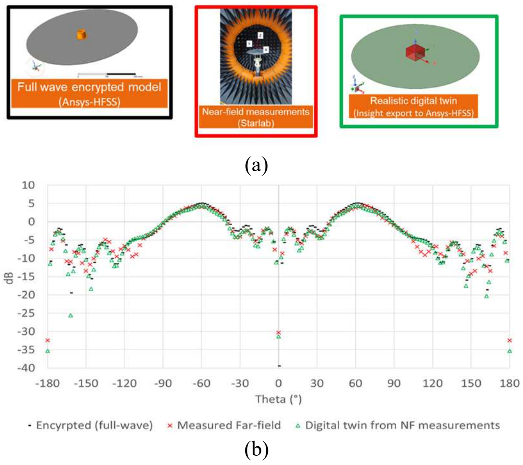
Fig. 1. (a) Case study C17 aircraft model in Ansys HFSS simulator environment with position of monocone antennas (MVG SMC2200) at two locations, (b) SMC2200 antenna with a 40cm ground plane flat plate measurement setup in MVG StarLab.

The same antenna was measured in the MVG Starlab near-field multi-probe measurement system [9] over a 40cm (diameter) flat ground plane plate as shown in Fig. 1(b). The measurement over a ground plane is very important in this study, because it enables to take into account the coupling between the antenna and the ground plane during the post-processing phase, where the equivalent current source reconstruction is done. The process of equivalent current source evaluation (or Huygen's Box, or near-field source) has been described in detail in [5]. The equivalent near-field source from measurements (or realistic digital twin) of the antenna is then exported to Ansys HFSS simulation tool, and placed on the same locations on the aircraft as shown in Fig. 1 a). The size of near-field source (L-40 x W-40 x H-28 mm) is slightly larger than the actual antenna size (L-30 x W-30 x H-23 mm). The 5mm extra length on each side of the antenna dimension corresponds to the $\lambda_0/20$ margin, that is the minimum recommendation in order to ensure the accuracy of the near-field source reconstruction process. This margin takes into account the antenna positioning errors during the measurements and avoids post-processing errors.

Before simulating the whole structure (aircraft with the two antennas) in Ansys HFSS, first the antenna full wave encrypted model and the near-field source are simulated alone using Finite Element Method (FEM) over an infinite ground plane. Then the simulated data is imported on to the aircraft and a Hybrid Shooting and Bouncing Rays (SBR+) solver is used. This solver is an asymptotic, ray tracing electromagnetic solver specially designed to simulate electrically large problems. It is a hybridization between Geometrical Optics (GO) and Physical Optics (PO). In addition, this solver permits to account for creeping waves, Wedge correction, and distortion of surface currents due to discontinuities using the physical theory of diffraction (PTD). The uniform theory of diffraction (UTD) is used to enhance the PTD in order to simulate the multiple bounces and allowing evaluation of creeping waves in the shadowed region [10].

III. Results

The first step is to compare the far-field directivity patterns obtained from the full-wave encrypted antenna model (reference) simulation, the near-field measurements, and the Huygens box obtained from the measurements and post-processing at 3 GHz (realistic digital twin). The three setups and corresponding results are shown in Fig. 2. All three antennas are placed on a 40cm ground plane in order for a just comparison. The directivity patterns are in excellent agreement, for peak directivity, side lobe levels, and null positions.



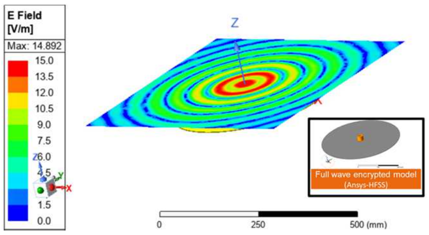
(a)

(b)

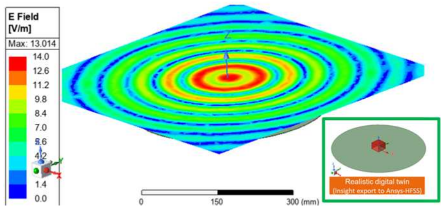
Fig. 2. (a) full-wave simulation setup of encrypted model, near-field measurement setup, and realistic digital twin simulation setup, at 3 GHz, (b) comparison between far-field directivity patterns at 3 GHz for the three cases with 40cm ground plane in azimuth = 0° cut-plane.

This step is important to have confidence in the accuracy of the realistic digital twin of the antenna. As mentioned in section I, as the complexity of the antenna grows and for higher frequencies, the digital twin (full-wave mode) accuracy can be difficult to achieve. Hence for more complex antennas, the realistic digital twin from measured data would allow us a better representation of the antenna.

The E-fields on the XY plane at 30mm above the antenna aperture, obtained from full-wave simulations of the encrypted model (reference case), and the realistic digital twin (from near-field measurements and post-processing) are compared in Fig. 3. Excellent correlation is observed between the two scenarios.



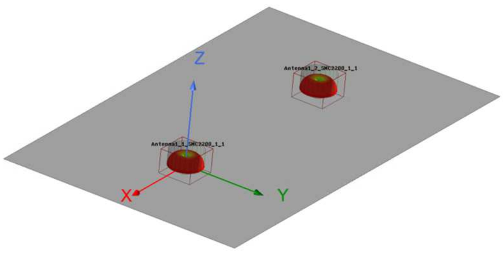
(a)



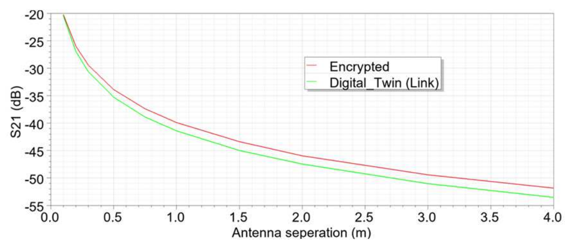
(b)

Fig. 3. E-fields on XY plane at 30cm above the antenna aperture from (a) full-wave encrypted model, and (b) from realistic digital twin at 3 GHz.

Next step is to study the coupling between two antennas placed on a finite rectangular ground plane. The distance between the center of the two antennas was varied from 0.1m up to 4m. The simulation setup is shown in Fig. 4 (a), and is the same for both antennas. The S21 coupling variation with distance is compared in Fig. 4 (b). The results are in good agreement overall. Specially when the antennas are in proximity to each other. The small differences for larger separation distances can be attributed to variations in simulation conditions (ray tracing).



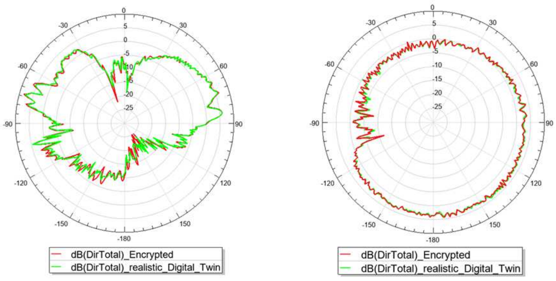
(a)



(b)

Fig. 4. (a) Coupling simulation between two antennas on a rectangular finite ground plane (b) S21 Results obtained from full-wave encrypted model and realistic digital twin w.r.t separation distance.

Once the antenna is validate over a small ground plane, the next step is to integrate it on the large aircraft model at top and side positions (Ant#1 and Ant#2 in Fig. 1(a)). The simulations are done in SBR+ mode (with Advanced creeping mode), in Ansys HFSS simulation environment using the full wave encrypted model and then the realistic digital twin from measured data.

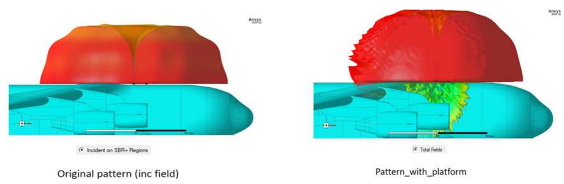


(a) (b)

Fig. 5. 1D radiation pattern phi = 0° cut-plane at 3 GHz comparison between full-wave encrypted model and realistic digital twin on the aircraft at (a) top position Ant#1 (b) side position Ant#2.

The radiation patterns directivity values, in phi = 0° cut-plane, are presented in Fig. 5(a) for the top Ant#1 and in Fig. 5(b) for Ant#2. Excellent agreement is observed between the reference case and realistic digital twin for both positions.

Next, the 3D far-field radiation patterns (directivity values), at 3 GHz are obtained from, the near-field realistic digital twin over an infinite ground plane, and from the antenna integrated on top location of the aircraft (Ant#1 in Fig. 1(a)), are compared in Fig. 6. By choosing the incident field only, we can visualize the antenna pattern alone (incident field over infinite ground plane), and by activating the total field, we can visualize the change of the antenna pattern with the effect of the aircraft, both in the same simulation window.



(a) (b)

Fig. 6. 3D far-field directivity pattern at 3 GHz for (a) incident field representing the top antenna alone over infinite ground plane (b) total field representing the antenna integrated on top of the aircraft.

IV. Conclusions

The use of near-field spherical measurements, for electrically small radiating elements, combined with advanced post-processing techniques (Link approach) permits the generation of realistic digital twin models. These models can then be mounted on, or integrated into, electrically very large structures in the full-wave electromagnetic solvers to optimize the antenna positioning, coupling with near-by sources, EMC issues, and hence ensure the best quality of service of the whole system. A small monocone antenna working at 3GHz was used in this study. The full-wave encrypted model and the realistic digital twin provides very close agreement in terms of far-field directivity patterns obtained over a small flat ground plane (of 40cm diameter). The E-field distribution in the proximity of the antenna are in excellent agreement between the reference case and the digital twin from Link. The coupling over a finite ground plane with different separation distances between the two antennas in both cases (reference and digital twin) is very similar from 0.1m up to 4m separation distance.

Finally, the antennas are integrated on the curved areas of the aircraft at two different locations. The antenna far-field directivity patterns are clearly modified due to integration location on the aircraft. Both the reference case and the Digital twin (Link) models provide similar results and thus validate the Link approach to simulate very large structures, even for curved surfaces.

The Link approach to generate the realistic digital twin is extremely helpful at the early stages of the system integration design cycle, and avoids the deadlocks due to lack of availability of full-wave models of third party radiating modules. In addition, for higher frequencies, and complex antenna elements such as phased arrays, obtaining a precise full wave model is a challenging task. Thus, the realistic digital twin using measured data enables an accurate model of the radiating element, when its integrated on a large structure.

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