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A Hybrid Approach Using Near-Field Scanning in Combination with Field Simulations

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Abstract

This contribution shows the principle of near-field scanning (NFS) used in combination with electromagnetic field simulations across various domains of applications including automotive, IoT and industrial). With a near-field scanner, the field probes capture the electric and magnetic field strength within a few milli- or centimeter distance to the device under test (DUT). One the one hand, the near-field scanning results can be directly used in order to characterize and to investigate the DUT regarding functionality, security, electromagnetic compatibility (EMC), electromagnetic immunity (EMI) and field propagation characterization. On the other hand, using the so-called Huygens-principle, equivalent near-field sources of the DUT can be derived from near-field scans. These sources can then be imported into a field simulation tool to further post-process the NFS results. This hybrid approach can be used to extrapolate the near-field into the far-field at e.g. 3 meter or to evaluate the influence of the DUT on the environment and adjacent devices (cars, airplanes, humans, housing, others devices). It will be shown, that near-field scanning is a beneficial technique in every design phase of an electric component all along the way until its integration into the whole final system.

Key words: Near-Field Scanning, Field Simulations, EMC, EMI, Huygens-principle

Introduction

The trend towards electrification and digitalization is becoming increasingly important for all industries and daily life. Higher frequencies, increasing integration factors and the smartification of all devices lead to an increasingly crowded electromagnetic spectrum throughout the place. This fact leads to increasing electromagnetic interference (EMI) between different components and systems and their close environment. [1] Especially in the transportation sector, electrification of vehicles, vessels or airplanes is one of the dominant topics as politicians and industry try to reduce the carbon footprint and the consumption of fossil energy sources. However, electronic systems and components cover a wide range of possible operating points, ranging from very low power to kilowatts of power and from low frequencies to high frequencies. On the one hand, 77 GHz radar modules and 5G communication are used for autonomous driving, while on the other hand, motors and battery chargers operate at a few tens or hundreds of kilohertz and power from 11 kW to a few hundred kilowatts.

To avoid interference with other devices, each subsystem must be tested for electromagnetic compatibility (EMC). In addition, the EMC compliance of the overall system must be tested under realistic operating conditions (e.g. in a fully equipped car). These component tests are often based on conducted measurements for cable-induced problems or far-field measurements for radiation-based problems. To get a quick, simple and comprehensive overview of the EMC characteristics of such devices, these test methods are good and sufficient. When such tests fail, manufacturers and developers start troubleshooting only based on these results, which usually do not provide any concrete information about the cause of the problem. Moreover, this very often ends in a trial-and-error approach, as EMC problems usually vary from one application to the next.

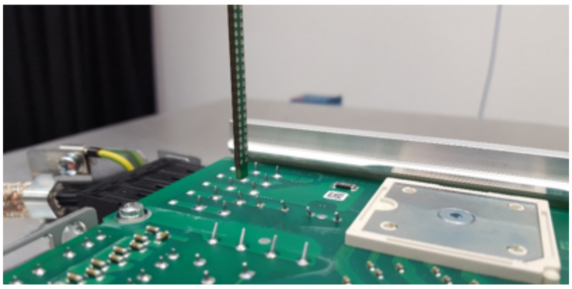

Figure 1. Example of a near-field measurement

This is where near-field scanning (NFS) based test methods can help. Traditionally rooted in antenna testing, NFS has evolved to address these critical issues. By using a near-field scanner to measure the electric and magnetic field strengths in close vicinity (typically within millimeters or centimeters), a detailed insight into the electromagnetic behavior of the device-under-test (DUT) is obtained. This gives developers immediate feedback on issues such as noise sources, malfunctions, coupling paths and safety aspects. [1,2]

In addition to evaluating the pure NFS results, equivalent near-field sources of the test specimen can be derived using a near-field scanner. These can be used in electromagnetic (EM) field simulation tools for advanced post-processing. Using the surface equivalence principle, the tangential near-fields must be recorded on a closed surface around the test object, which then forms the near-field source, also known as the Huygens surface [3]. This source has the same EM properties towards its outer space as the original measurement object. Various investigations can be carried out with such a field source. The simplest is far-field extrapolation, which provides a prediction of the far-field behavior and can therefore estimate the results of EMC-compliant measurements [4].

Furthermore, the integration of additional devices, systems, components, enclosures, vehicles or other units into the simulator significantly improves the utilization of the near-field source. This enables the evaluation of the electromagnetic effects of the DUT on its environment in terms of EM susceptibility, radiation optimization, positioning of the DUT in its intended environment and various other factors [5].

Near-Field Scanning and the Huygens-Principle

Near-Field Scanning

In general, a near-field scanner consists of a positioning robot, a measurement receiver (for near-field sources: dual-channel for phase-related measurements) and near-field probes. Additional components such as a 3D scanner and peripheral devices can be integrated to improve system accuracy and automation. A Cartesian-based scanner, for example, usually has at least four probes: tangential (x, y) and normal (z) probes for H- and E-fields. While a spectrum analyzer is sufficient for pure amplitude measurements, a two-channel concept is required to obtain phase information, each of which has its own advantages and disadvantages. Such a near-field scanner, such as the NFS3000 from Fraunhofer ENAS, is used for the measurements examined in the following chapters.

Huygens-Principle

The transformation of the near-field into the far-field can be described using the surface equivalence theorem, also known as Huygens' principle. This principle states that every point on a propagating electromagnetic wave can be considered a source of a new electromagnetic wave. Based on this concept, a set of equivalent sources positioned on a closed surface around the DUT can determine the device's electromagnetic radiation in the far-field. The space surrounding the DUT, which is filled with homogeneous, linear, and isotropic material, is referred to as D_0. This space is divided into two regions, $D+$ and $D-$, by the enclosing surface S, as illustrated in Figure 2.

The equivalent sources on this surface S are defined by the fictional magnetic current density M and the fictional electric current density K. Each of these densities can be expressed by their related tangential electric or magnetic near-field, which are defined as

$$\vec{K} = \vec{n} \times \vec{H}|_S \, ,$$

$$\vec{M} = \vec{n} \times \vec{E}|_S \, .$$

This means, that the surface-equivalence-theorem is a good and easy way to use near-field scanning data as an equivalent field source, which can replace the DUT in the inner region of S. For NFS systems, usually working with a cartesian coordinate system, the surface S has the shape of the box. Therefore, it is often and from now on called Huygens-Box.

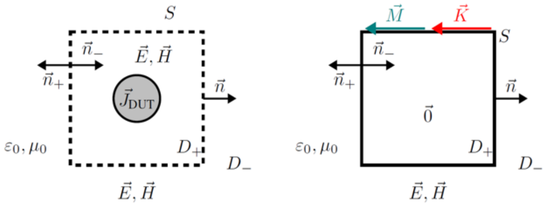

Figure 2. Basic principle of the surface equivalence theorem [5]

Having the current densities at hand the electric and magnetic field in the area D_- can be calculated using the STRATTON-CHU equations. With k_0 as free-space wave number and Z_0 as wave impedance in free-space the electric field can be represented by

$$\vec{E}(\vec{r}) = -jk_0 Z_0 \vec{A}_e(\vec{r}) - \nabla \Phi_e(\vec{r}) + \nabla \times \vec{A}_m(\vec{r}), \vec{r} \in D_-$$

and the magnetic field is defined as

$$\vec{H}(\vec{r}) = j\frac{k_0}{Z_0}\vec{A}_m(\vec{r}) - \nabla\Phi_m(\vec{r}) + \nabla \times \vec{A}_e(\vec{r}), \vec{r} \in D\_ \text{ .}$$

The electric and magnetic vector potentials

$$\vec{A}_e(\vec{r}) = \int_S G_0(\vec{r},\vec{r}')\vec{K}(\vec{r}')dA(\vec{r}') \text{ ,}$$

$$\vec{A}_m(\vec{r}) = -\int_S G_0(\vec{r},\vec{r}')\vec{M}(\vec{r}')dA(\vec{r}') \text{ ,}$$

$$\Phi_e(\vec{r}) = j\frac{k_0}{Z_0}\int_S G_0(\vec{r},\vec{r}')\nabla_S \vec{K}(\vec{r}')dA(\vec{r}')$$

and

$$\Phi_m(\vec{r}) = j\frac{1}{Z_0 k_0}\int_S G_0(\vec{r},\vec{r}')\nabla_S \vec{M}(\vec{r}')dA(\vec{r}')$$

complete the set of equations, whereas ∇_S is the tangential NABLA operator and G_0 is the GREENs function. Solving this equation system e.g. the boundary element method can be used, which was shown in [1] and [6]. In [6] also an approach to use only magnetic near-field components for the far-field calculation were examined. For the results within this publication, electric and magnetic fields are used.

Near-Field Scanning Application

Basically, near-field scanning results are evaluated with respect to the corresponding location at the DUT to find any issue related to EMC, functionality or security. The following two examples will show different purposes to use NFS results.

Solving EMC an issue

One of the main reasons for using electro-magnetic near-field scanning is to detect EMC problems. These can be unexpected electrical or magnetic hotspots caused, for example, by unwanted antennas, unsuitable component selection and design or poor routing and coupling on the PCB. Especially for DC-DC converters with high currents and voltages, the output filter must be designed very carefully, as even relatively small ripples can cause conducted or radiated EMC problems that lead to failing the compliance tests.

The following example shows such an output filter of a DC-DC converter for an on-board car charger. The converter operates at a frequency of several tens of kHz and the first version had problems with conducted interference. Figure 3 shows the near-field results of the normal electric field E_z. On the right side, the output filter (between x = 500 and 600 mm) ends at about x = 500 mm. To the left of x = 500 mm, however, there is still a considerable amount of alternating fields, which should ideally be filtered down to direct current. From the near-field scan, it is possible to deduce where the filter is not working properly.

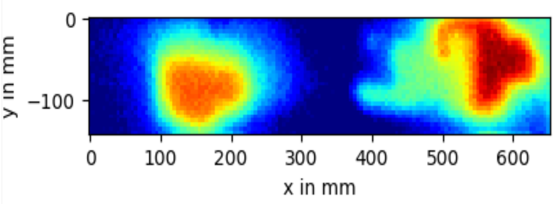

Figure 3. Measurement of the DC-DC converter with EMC issue

Utilizing these results, the filter can be redesigned and improved based on near-field measurements instead of using trial-and-error approaches to improve the EMC behavior. The result of the new version is shown in Figure 4. There, the electric field is much smaller at x = 400 to 500 mm. The EMC test carried out was also subsequently passed.

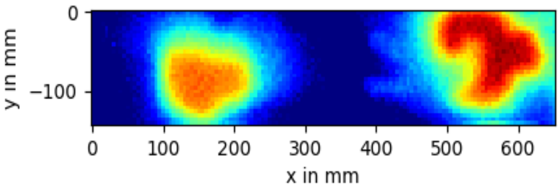

Figure 4. Measurement of the DC-DC converter after redesign

Functional Analysis

The second example shows a 2.4 GHz antenna test board, which is shown in Figure 5. This is one of the standard antennas for IoT applications with WiFi or Bluetooth connectivity. The PCB design is imported into the 3D field simulation tool CST Studio Suite. On the one hand, it is simulated and the H-field at 2.4 GHz and at a distance of 2 mm is examined. On the other hand, the H-field is measured the same points using the NFS3000 near-field scanner. For validation purposes and to check the functionality of the antenna, simulation and measurement are compared with each other.

Figure 5. 2.4 GHz antenna test board

The results are shown in Figure 6. It can be seen that both results are looking quite similar, and therefore measurement and simulation can be considered equal. In numbers it is a root mean square error of 4% over the measured space.

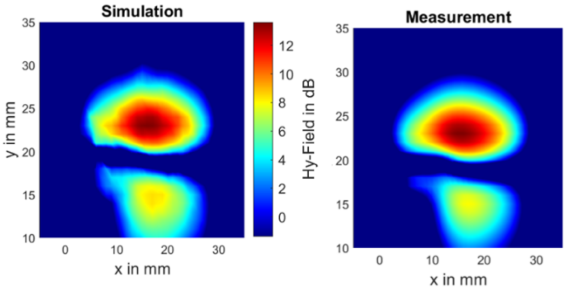

Figure 6. Measurement and simulation of antenna test board

Combination with Simulations

Using the Huygens-principle described before, near-field scanning results can used within electromagnetic field simulation tools. For this purpose, CST Studio Suite will be used. This hybrid approach combines measurement results with field simulations to give an added-value to the near-field scanning technique. It can be used for different purposes, which will be shown in the following examples.

Device-under-Test

The Universal Spherical Dipole Source (USDS) from Applied Electromagnetic Technology is used as a test specimen to validate the broadband far-field transformation. The USDS, a spherical dipole antenna with a diameter of 10 cm, emits dipole-shaped fields from 10 MHz to 16 GHz. It has an internal comb generator with selectable frequencies (10, 64, 100 and 133 MHz) and is powered by a rechargeable battery to avoid cable interference. The USDS is primarily used for EMC-related characterization and shielding effectiveness testing.

The USDS is placed on Styrodur panels to minimize electromagnetic interference from the metal base plate of the NFS3000. The Styrodur cut-outs have a height of 15 cm to reduce the influence of the base plate of the near-field scanner. The comb frequency is set to 10 MHz. Measurements are taken on a Huygens-box around the USDS, with a minimum distance of 1 cm to the sphere. The cubic measurement box with an edge length of 12 cm has points at a grid distance of 1 cm, a total of 169 points per field component per side. Only the tangential field components are measured for the far-field transformation. To measure the bottom-side the sphere is mirrored to obtain a six-sided measurement. The spectrum is measured from 50 MHz to 1 GHz.

Near-Field to Far-Field Extrapolation

The simplest application of a near-field source is the simulation of the far-field. For antennas, this provides information about the radiation behavior such as directivity and total radiated power. In EMC assessment, the far-field simulation helps to estimate EMC conformity for measurements in an anechoic chamber.

The measurement results of the Huygens-box are presented below. Figure 7 shows the magnetic field strength and Figure 8 shows the electric field strength, both at 300 MHz. The distance between the USDS and the base plate is 15 cm for these measurements. The results of the magnetic field are quite comparable with the simulation results shown in Figure 7. The results of the tangential electric field are in line with the expectations for a dipole antenna. In addition, the near-field data on the box are symmetrical to the axis of rotation of the USDS.

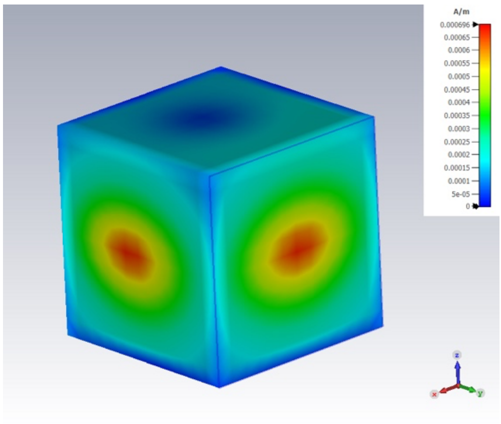

Figure 7. Measurement of the tangential magnetic field strength on the Huygens-Box at 300 MHz

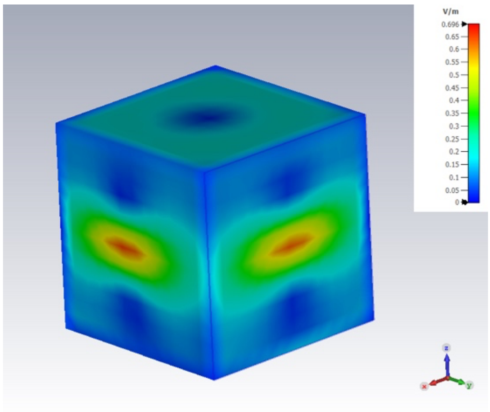

Figure 8. Measurement of the tangential electric field strength on the Huygens-Box at 300 MHz

The near-field data is now transformed into the far-field at a distance of 1 meter. The theoretical principles have already been discussed. A special solver developed in [6] deals with the equations for NFS Huygens-box measurements. For the following analysis, the CST integral solver (with the boundary element method) is used due to its advanced post-processing capabilities. The Huygens-box measurements are imported and simulated for each frequency. A far-field monitor at 1 meter distance is defined to obtain the E-field in dB(µV/m), which later facilitates the comparison with measurements in an anechoic chamber.

Figure 9 compares the transformation results with measurements in an anechoic chamber. The figure shows that both sets of results agree well in terms of data quality and quantity. The overall pattern of the transformation closely follows the measurement peaks, and the local minima at 230 MHz and 410 MHz are accurately reproduced. The maximum error occurs at 870 MHz, with a difference of 5 dB, while the mean error is around 2 dB. This evaluation shows that the far-field transformation from near-field scan data for highly radiating devices is very effective and comparable to far-field measurements.

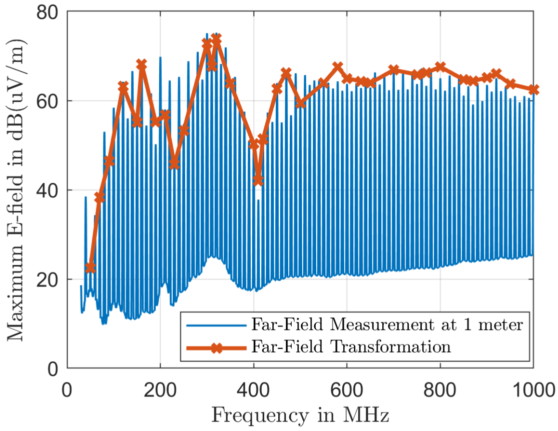

Figure 9. Comparison of far-field measurement in an anechoic chamber with the near-field to far-field transformation

Radiation Inside a Car

In addition to simply using the near-field source to predict far-field radiation, it can also be used in 3D field simulations. The source can be imported and placed anywhere in a given environment, e.g. in cars, enclosures, halls and so on. In the last two examples, the radiation of the USDS is shown inside and outside a simplified model of a car.

The car model is made of only three materials. The chassis is made of a perfect electrical conductor (PEC). The main internal parts are made of plastic and the wheels are made of rubber. It is sufficient at this point to demonstrate the basic concept of using near-field sources. For real problems, of course, a more detailed model of the vehicle would be required to achieve the most accurate results.

For the first demonstration, the near-field source is placed in the vehicle near the entertainment system (see Figure 10). This may represent an electromagnetic interferer causing EMI problems inside the vehicle. The evaluation frequency for this and the next case is f = 500 MHz. A representative result of the simulation is shown in Figure 11. It shows the electric field on a cross-section of the vehicle. The source with the highest field strength is clearly visible. Most of the radiation goes beyond the windshield or remains in the passenger compartment, but a considerable proportion of the electric field is also present at the headlights and rear lights.

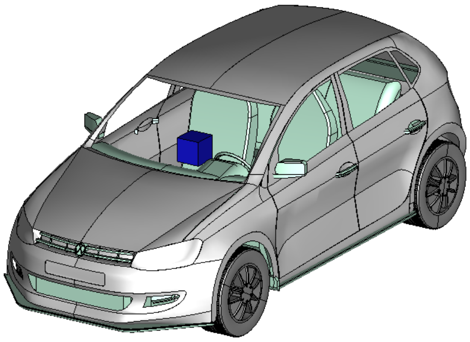

Figure 10. Simplified car model with near-field source inside

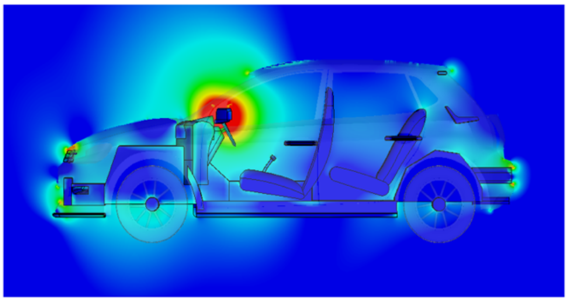

Figure 11. Simulation of radiation inside the car

The conclusion for this case is that if a component with EMC problems or even intended radiation is placed inside the vehicle, it can also interfere with parts further away. The simulation can help to replace the component, place or improve the shielding of the component itself or other sensitive parts, or even improve the positioning of these sensitive components.

Radiation Outside a Car

In addition to EMI cases, intended radiation is also of great importance in the automotive sector. Communication and radar sensors must function well and reliably to enable a safer driving experience and future autonomous driving. By placing the near-field source, e.g. at the front or on the roof of the vehicle, the radiation into the environment can be evaluated to optimize the positioning and function of the subsystems.

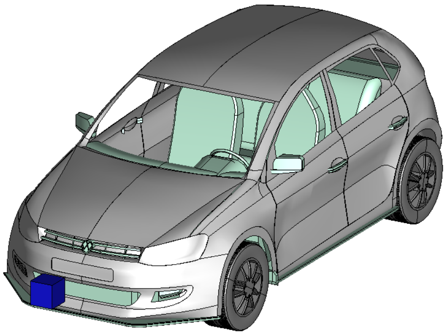

Figure 12. Simplified car model with near-field source outside

In Figure 12, the near-field source is positioned at the front of the vehicle and represents a type of sensor system that is intended to radiate. Here too, the evaluation frequency is f = 500 MHz. The results for this simulation are shown in Figure 13. Here, too, the cross-section of the vehicle and the corresponding electric field at 500 MHz are shown. The radiation of the device placed on the car can be assessed on the basis of the field distribution. Reaction effects could improve or worsen the desired directivity, which can be compared with the directivity without a car, for example.

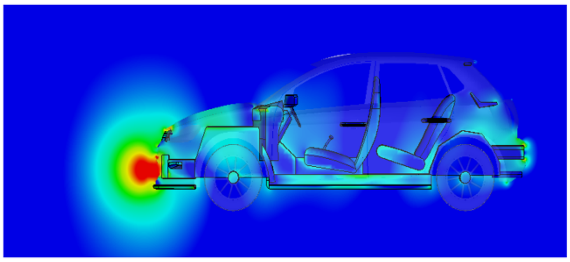

Figure 13 Simulation of radiation outside the car

Conclusion

To conclude, this paper emphasizes the benefits of near-field scanning in automotive applications by presenting the results of near-field scanning for different DUTs and demonstrating their benefits for different use cases. The effectiveness of addressing EMC issues and performing functional analysis is demonstrated. Using the Huygens principle, a near-field scanner captures near-field sources that can be seamlessly integrated into field simulation tools. This hybrid methodology significantly expands the field of application and the added value of this technique. Three different use cases integrating measurement and simulation were presented: a basic extrapolation from near-field to far-field and two scenarios illustrating radiation effects both inside and outside a vehicle.

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