SIMULATION-BASED VALIDATION OF NEAR FIELD COMMUNICATION EFFECTS ON AIRCRAFT WIRING

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Abstract
Near Field Communication (NFC) is a wireless technology commonly utilized in Portable Electronic Devices (PEDs) and contactless smart cards. NFC technology is characterized by the following two attributes: a tangible user interface and secured short range communication. The International Air Transport Association (IATA) has announced this technology to be an enabler for the future of digital travel with dedicated NFC touch points at the airport and within the aircraft. An exhaustive integration of NFC interfaces into the aircraft cabin, however, still remains a challenge. There is currently a lack of explicit qualification guidelines for electromagnetic compatibility (EMC) testing in an aircraft environment at the NFC frequency of 13.56 MHz. To overcome this challenge, the following paper presents a measurement setup for generating and evaluating magnetic fields according to the current NFC standards. This setup has been characterized with a magnetic field probe and via an elaborated simulation model using the CONCEPT-II software, an electromagnetic field simulator. NFC effects on aircraft wiring have been investigated under different coupling conditions and measuring scenarios have been validated with the simulation model.

1 INTRODUCTION
In 2013 and 2014 the Federal Aviation Authorities (FAA) and the European Aviation Safety Agency (EASA) allowed airlines to expand the use of Portable Electronic Devices (PEDs) [1]. Consequently, the number of passengers using PEDs during all phases of flight is constantly increasing. The majority of these PEDs are equipped with an NFC interface by default. An exhaustive integration and use of tangible NFC interfaces
in the aircraft cabin for crew support, passenger self-service, and payment applications still remain a challenge due to the lack of an explicit qualification guideline for electromagnetic compatibility (EMC) testing in an aircraft environment. In contrast to other Radio Frequency (RF) communication technologies, e.g. WiFi or GSM, operating in the far field and already certified for use in the cabin, NFC is working at a frequency of 13.56 MHz to exchange data via electromagnetic induction in the near field region. The physical layer of NFC communication is defined by the non-aviation standard ISO/IEC 18092 [2], using a magnetic field strength $H_{\text{max}}$ up to 7.5 A/m (rms).

Investigations on existing aircraft standards to perform RF emission testing and correlating them to NFC technology led to an EMC testing methodology, which was proposed in a recent 2016 publication [3]. With a test setup (cf. Figure 1) for inductive coupling measurements, a total number of 19 NFC-equipped smartphone and tablet devices were characterized in a realistic aircraft cabin scenario and tested against the RTCA DO-160G aviation standard [4]. The varied, repetitive measurements with these commercial-off-the-shelf PEDs have clearly shown that in the chosen coupling scenario none of the PEDs were able to induce a current into the aircraft wiring higher than approximately 6 mA [3]. In DO-160G Section 20 [4] the qualification levels for current induction are defined. As aircraft equipment is qualified against category T (CAT T), which specifies the maximum allowed induced current to be 7.5 mA, none of the tested PEDs were above this limit, even when touching an unshielded cable. This observation should mainly result from the fact that PEDs have limited battery power and thus produce a moderate power output at the RF frontend. The magnetic fields of PEDs used for communication in the near field do not reach the maximum value of specified magnetic field strength $H_{\text{max}}$.

![Figure 1 – Test setup for EMC testing of T-PEDs (a) and determination of maximum induced current by raising, sliding, and rotating a T-PED close to an unshielded cable (b) [3]](image-url)

In a 2006 paper using analytical calculations as well as a simulation method for the analysis of an induced transient current in a conductive wire the authors have concluded that “particularly loop structures are being sensitive to the influence of magnetic fields at this frequency range” whereas “linear conductors are less sensitive” [5]. Despite this inexplicit summary of the authors, no further work on the effects of NFC on aircraft wiring was published. The still insufficient results of the two existing papers [3, 5] clearly indicate that further investigations should be performed in order to gain a more comprehensive understanding of NFC effects on aircraft wiring.

Therefore, in this paper a physical measurement setup for generating and evalu-
ating magnetic fields according to NFC standards is transferred to a simulation model. The abstraction level of the model reflects all fundamental parameters of the real system, both electrically and mechanically. Model validation is carried out via calibration measurements and comparing them to the simulation results and the data sheet of the loop antenna. The simulation model is subsequently used to evaluate potential worst case coupling scenarios of NFC emissions in aircraft wiring.

2 MEASUREMENT SETUP

The EMC emission test setup used in this paper (cf. Figure 2 and 3) is correlated to the methodology for EMC testing as proposed in [3]. The setup represents a combination of two DO-160G [4] test arrangements, i.e. of the injection probe insertion loss test setup (cf. DO-160G, Figure 20-4) and the conducted susceptibility test setup (cf. DO-160G, Figure 20-9). An unshielded cable with a cross section of 1.0 mm$^2$ is utilized as the cable under test (CUT). The cable serves as an example of aircraft wiring and is positioned 5 cm above a ground plane. On one side it is grounded with a 50 Ω terminator and on the other side connected to an oscilloscope with built-in impedance of approximately 50 Ω. A loop antenna with a monitor output is powered by an RF amplifier and is used to generate a well-defined magnetic field strength up to 7.5 A/m (rms) to influence the CUT in a controlled manner.

![Figure 2 – Measurement setup for inductive coupling tests [3]](image)

The antenna used for the measurements is a Schwarzbeck HFRA 1356, a matched transmitting loop antenna operating at 13.56 MHz. With a diameter of $d = 250 \text{mm}$ it can be categorized as small loop antenna ($d < 1/10\lambda$). With its two turns, the antenna is specified and capable of producing a magnetic field strength of up to 10 A/m in the center point of the antenna. A monitor output allows the continuous tracing of the magnetic field because the voltage at the monitor output is proportional to the generated magnetic field.
NFC utilizes an amplitude-shift keying (ASK) with a modulation index of typically 8% to 30% for communication. Hence, for coupling investigations at upper limits a plain sine wave signal with 13.56 MHz is adequate. The signal is provided by a Tektronix AFG3051C signal generator and amplified with the high gain power amplifier AR 5W1000 from Amplifier Research which is capable of generating 5 W of continuous waveform to power the loop antenna. For data acquisition the monitor output of the antenna and the CUT are connected to the inputs of a Tektronix MDO4054-3 mixed-domain oscilloscope with an impedance of 57 Ω at 13.56 MHz. All entities of the measurement setup, i.e. the loop antenna, the CUT on the ground plane, the oscilloscope, and the signal generator with the amplifier, are shown in Figure 3.

Figure 3 – Entities of the measurement setup

3 ABSTRACTION OF SIMULATION MODEL

In contrast to dedicated measurements of individual coupling scenarios, an effective and efficient approach to assess NFC effects on aircraft wiring is the modeling and simulation of real system behavior. With the CONCEPT-II software [6] it is possible to model, simulate, and analyze electromagnetic fields. The software is based on the method of moments, a highly efficient calculation method that enables a user to simulate smaller and medium-sized models on an ordinary desktop workstation.

Based on the measurement setup described in the previous section a conceptual model was abstracted to identify the key elements for modeling real systems with NFC coupling scenarios. According to Robinson, a conceptual model is defined as a description of a computer simulation model without having specific software in mind [7]. The problem at hand can be categorized as a purely electromagnetic problem. Moreover, the used antenna type is familiar and well understood with regard to its construction and principles of operation allowing basic physical laws to be used for abstracting a correct model.

The conceptual model of the measurement setup is given in Figure 4a. It consists of three components: the small loop antenna with input parameters as the core component, the CUT, and the ground plane. This conceptual model is used as a reference to verify the creation of the simulation model [8]. Key points for validation of the simulation model against the real system antenna behavior are the generated magnetic field values, i.e. the values of magnetic field strength and gradients have to match on both real system and simulation model.
Since the antenna is the most important component of the model, the antenna parameters were estimated analytically. The loop antenna was abstracted to a circuit as shown in Figure 4b, forming an RLC circuit.

\[ X = X_L + X_C = \omega L_{Ant} - \frac{1}{\omega C_{Comp}}; \quad \omega = 2\pi f \]  

When tuning an ideal antenna the reactance \( X \) ideally would approach zero. This is difficult to achieve for a real antenna configuration. Nevertheless an analytical investigation is a good starting point for understanding and tuning the antenna model and to determine the initial conditions of the simulation model. The inductive reactance \( X_L \) is only dependent on the radius of the antenna loop \( r = 125 \text{ mm} \), the number of turns \( n = 2 \), the radius of the antenna wire \( R = 0.5 \text{ mm} \) and the fixed frequency \( f = 13.56 \text{ MHz} \) [9]:

\[ X_L = 2\pi f n^2 \mu_0 r \left[ \ln \left( \frac{8r}{R} \right) - 1.75 \right] = 313.2 \Omega; \quad \mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \]  

The capacitance \( C_{Comp} \) to compensate \( L_{Ant} \) \( (X_C = X_L) \) can be calculated by using Equation 1 and Equation 2:

\[ C_{Comp} = \frac{1}{\omega X_L} = 37.47 \text{ pF} \]  

With the reactance being minimized the remaining factors for voltage and current in the antenna are the resistances \( R_{Rad} \) and \( R_{Loss} \). The radiation resistance \( R_{Rad} \) is defined [10] as:

\[ R_{Rad} = 31200 \left( \frac{nA}{\lambda^2} \right)^2; \quad \lambda = \frac{c}{f} \]
$R_{\text{Rad}}$ is generally low on loop antennas due to the low ratio of covered area $A$ and wavelength $\lambda$. The loss resistance $R_{\text{Loss}}$ is typically set to 50 $\Omega$ in order to match the line impedance of most RF systems. By comparing both radiation and loss resistance, the radiation resistance becomes negligible in the overall context:

$$1.28 \cdot 10^{-3} \Omega = R_{\text{Rad}} \ll R_{\text{Loss}} = 50 \Omega$$

Therefore only $C_{\text{Comp}}$, $R_{\text{Loss}}$, and $L_{\text{Ant}}$ were used as the starting parameters for modeling. The radiated magnetic field strength is only dependent on the current in the antenna wire, and according to Ohm’s law it can be directly set by tuning the input voltage. For optimizing the antenna model, these values, i.e. voltage, current, and magnetic field strength, were used as a reference to verify that the numerical results are reasonable.

In the model the antenna wire was discretized into 67 sections in order to maintain accuracy while keeping calculation time short. The antenna model was completed by including a lumped resistor and conductance element, and an injector port for input voltage and frequency settings. An example with its resulting field distribution is shown in Figure 5 for a magnetic field strength of 1 A/m at the center point of the antenna loop. With the model of the small loop antenna, the central component of the conceptual model is now fully covered. The remaining two components, i.e. the CUT and ground plane (cf. Figure 4a) are considered at a later point. Before using the antenna model in coupling scenarios, a validation of the free space magnetic field strength distribution is mandatory. This can be achieved by a comparison of simulation results and measurement values.

Figure 5 – Simulation model with resulting magnetic field strength distribution

4 VALIDATION OF THE SIMULATION MODEL

The validation procedure focuses on the magnetic field strength distribution as the most distinctive key parameter, which is measured by Hall sensors. These sensors exhibit a linear output voltage response with respect to the strength of the permeating magnetic field. The used Hall sensor HZ552 from Rohde & Schwarz is a general purpose device and does not come with a calibration certificate. Thus, the user needs to empirically determine the probe’s specific conversion factor between magnetic field strength and output voltage. The Schwarzbeck HFRA1356 loop antenna described in Section 2 is
equipped with a monitor output enabling the user to control the magnetic field strength in the center point of the antenna. Additionally, the datasheet of the antenna provides a magnetic field strength gradient along the z-axis starting with 1 A/m at the center point (cf. Figure 5). A series of repeated measurements were performed in the center point and along the z-axis to determine the conversion factor of the probe (cf. Figure 6) by curve fitting. Next, the magnetic field strength of the antenna was varied. The response values of the probe were compared to the results of the simulation.

Figure 6 – Hall sensor probe in the center point of the loop antenna

Figure 7 depicts the datasheet values and a family of curves of both measurement and simulation results for magnetic field strengths of 1, 2 and 3 A/m at the center point. The measurement values are depicted as error bars and the simulation values are drawn as a spline function based on 5000 simulation points. The datasheet values for the antenna with magnetic field strength of 1 A/m at the center point are depicted as a dotted green spline function.

Figure 7 – Measured and simulated magnetic field strength values along the z-axis of the loop antenna for 1, 2 and 3 A/m at the center point

- Location of max. deviation
  - 2.1 ± 0.25 dbA/m
  - 2.9 ± 0.27 dbA/m
The characterization results prove the strong linearity of the Hall sensor response and the congruence of measured values with the simulation results. These results verify the conversion factor. Moreover, it is now possible to use the Hall sensor HZ552 as a magnetic field probe for absolute measurements in further applications.

5 COUPLING SCENARIOS

To achieve a more profound understanding of potential coupling effects, the simulation model was used to investigate several scenarios in which various positioning and routing of a CUT were analyzed. The objective was to detect and investigate possible worst-case configurations of NFC devices exhibiting a magnetic field strength of $H_{\text{max}} = 7.5 A/m$ in close proximity to aircraft wiring (cf. section 1). Following the work and the findings of Kürner et al. [5], straight and looped cable configurations were investigated. For this purpose the conceptual model was complemented with the pending components, i.e. the CUT and the ground plane (cf. Figure 4a). In parallel to the simulation it was possible to investigate coupling effects in the defined and characterized measurement setup. Foremost, to validate the overall simulation model, a full one turn cable loop with a diameter of 100 mm positioned centrically below the antenna (see Figure 8) was considered. The distances between the antenna and the CUT were varied.

![Figure 8 – Cable loop (d = 100mm) positioned below the loop antenna. Measurement setup (a) and simulation model (b)](image)

Further scenarios included a full one turn cable loop and a half turn cable loop with varied diameters as well as a straight cable positioned tangentially to the antenna loop. To be comparable with the antenna datasheet, both the measurements and the simulation were initiated at a magnetic field strength of 1 A/m at the antenna center point. The left side of Table 1 compares the obtained measurement results to the simulation values at varied distances along the z-axis. Scenarios with $H_{\text{max}} = 7.5 A/m$ at the antenna center point are shown on the right side of Table 1. These latter values were determined by simulation only because the power capabilities of the measurement setup were not sufficient to physically reproduce these scenarios. Resulting values of the induced current below the permissible CAT T limit of 7.5 mA according to DO-160G [4] are given in green.
Table 1 – Comparison between simulation and measurement values for different scenarios

<table>
<thead>
<tr>
<th>Mag. field strength</th>
<th>1 A/m @ antenna center point</th>
<th>7.5 A/m @ antenna center point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>Straight cable</td>
<td>250 mm</td>
</tr>
<tr>
<td>Dist. [cm]</td>
<td>½ loop</td>
<td>full loop</td>
</tr>
<tr>
<td>2</td>
<td>6.3 (6.0)</td>
<td>10.9 (10.8)</td>
</tr>
<tr>
<td>5</td>
<td>3.9 (3.8)</td>
<td>5.7 (5.7)</td>
</tr>
<tr>
<td>10</td>
<td>2.1 (2.1)</td>
<td>2.9 (2.9)</td>
</tr>
<tr>
<td>15</td>
<td>1.3 (1.3)</td>
<td>1.5 (1.5)</td>
</tr>
<tr>
<td>20</td>
<td>0.8 (0.8)</td>
<td>0.8 (0.8)</td>
</tr>
</tbody>
</table>

Figure 9 depicts two resulting magnetic field distributions obtained with the simulation model and the loop antenna. The antenna generating a magnetic field strength $H_{\text{max}} = 7.5\,\text{A/m}$ at the center point is positioned 5 cm above the cable configuration. It is important to note that although having completely different configurations (straight vs. loop), the induced currents are comparable (see Table 1: 29.5 mA vs. 34.2 mA). Depending on the distance of the antenna, another noticeable effect is the increasing influence of the ground plane (cf. Figure 9). The closer the antenna is moved to the plane the more the magnetic field is reciprocally affected by the induced ground plane currents.

![Figure 9](image_url)

Figure 9 – Simulated magnetic field distribution in coupling scenarios for 7.5 A/m and an antenna distance of 5 cm with a straight wire (left) and a 100 mm diameter cable loop (right)

6 CONCLUSION

Many series of measurements and simulations with varied configurations were carried out and compared against each other. A well-defined and characterized measurement
setup was used to perform the physical investigations. In all cases a perfect match of measurement and simulation results were obtained. These results clearly prove that the simulation accurately models the physical setup. The model allows an effective and efficient assessment of NFC effects on aircraft wiring and can be used for evaluating further coupling scenarios, even beyond the operational limits of a physical measurement setup. Exceeding the simulation work of an earlier publication [5], this work provides a comprehensive understanding of NFC coupling effects on aircraft wiring using the CONCEPT-II software, an advanced electromagnetic field simulator for the numerical computation of radiation and scattering problems in the frequency domain. Further work will focus on simulating previous measurements with commercial-off-the-shelf PEDs [3] and establishing the measurement setup and a simulation model as acceptable means of compliance for certification of NFC devices in the aircraft cabin.

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