

Electromagnetic Analysis and CAD Modelling of an RF-ID System

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Abstract- Radio Frequency Identification (RF-ID) is a key technology in today's logistics and industrial scenarios, used for labelling and tagging items in warehouses and industrial production. In order to avoid unexpected faulty behaviours, some working conditions and setup parameters of RF-ID systems need to be carefully checked. To this aim, both measurements and numerical simulations can advantageously be performed. In this paper, some key working conditions are described and analyzed in terms of coupling between the reader device and RF-ID tags. In particular, the reading range in space of a standard inductive coupling 13.56 MHz RF-ID system is analyzed by using numerical simulations of scattering parameters and computer aided design (CAD) modelling. The purpose is to present an example suggesting how to efficiently perform such a kind of analysis in order to verify the effectiveness of a RF-ID system setup.

I. Introduction

Radio Frequency Identification (RF-ID) systems are quickly becoming a key application in several industrial and commercial environments, due to their particular flexibility [1]. In particular, areas such as logistics, warehouse management and industrial production are leading to a fast growth of RF-ID systems and related technologies. In the next years, RF-ID will become the definitive solution for labelling, tagging, tracking and identification in the above stated areas. Among all RF-ID technologies available, the one based on inductive coupling working at the standard High Frequency (HF) of 13.56 MHz is specially preferred due to its relatively low cost and small size, as well as robustness and flexibility. Simple yet effective construction techniques make the inductive coupling RF-ID a robust and cheap solution, suitable for several applications.

The main issue to be solved during the design and setup of an RF-ID system is to check the reading range, which varies from system to system and is strongly dependent on the setup. Such an analysis can advantageously be used both to verify the correct working conditions of the system, and to predict the occurrence of possible system failures, *e.g.* erroneous readings. It can be performed in two manners: through measurements or simulations.

Up to now, no accurate techniques have been developed to predict the behaviour of an RF-ID system. Some analytical calculations can predict the behaviour of the setup, describing the EM coupling necessary for the reading. Nonetheless, these models usually do not take into account the non-ideal effects of the environment in which the system operates [2]. Therefore, the provided results are often meaningless and do not reflect the true working operation of the system. By using numerical EM simulation tools, it is possible to predict the reading range of these systems including even several environmental effects and keeping into account variables and non-ideal conditions, thus being able to consequently design the system to fulfil the desired function. In [3] an interesting model is presented based on the use of the HFSS simulation software tool, from Ansoft Corp. This model follows a quite different approach with respect to the basic analytical treatment in [1], and shows drawbacks when real-world structures are considered. In particular, the simulation results are limited to a single-line geometric displacement between RF-ID system reader and tag coil. In [4], [5] and [6], the downsides of the analytic model are highlighted and a numerical approach is chosen. Nevertheless, in these papers, a comprehensive description of the system reading range is not given and a scattering (S) parameter analysis is not performed and used as an evaluation tool.

In this paper, the working conditions of a standard inductive RF-ID system operating at 13.56 MHz are analyzed by using a numerical simulation approach. In particular, an analysis based on S-parameters

and computed aided design (CAD) modelling is conducted on a two-port numerical model, and the parameter $S_{2,1}$ is analyzed to describe the necessary coupling between the reader device and the tag. The aim of the paper is to describe an example suggesting how to efficiently analyze the working conditions of an RF-ID system with special regard to the spatial reading range of the reader device. Three dimensional (3D) plots of EM field emissions and reading range obtained from simulations are finally provided.

II. Description of the system

An HF RF-ID system is a set of one or more reader devices (or interrogators) and one or more tag units communicating with each other through suitable coil antennas. An important issue in the setup and deployment of RF-ID systems is the characterization of some physical parameters of the system, such as, for instance, the distances and angles between the tag and the reader unit antenna at which the system correctly operates. An example of a generic couple of reader and tag coils is sketched in Fig. 1.

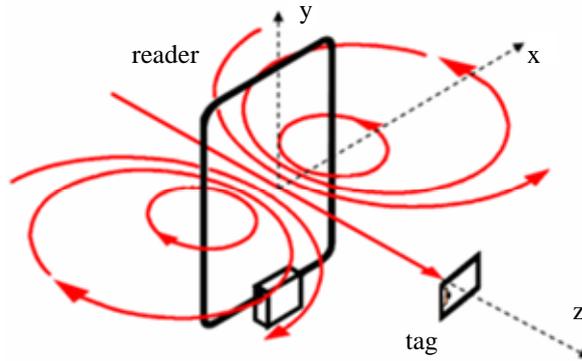


Figure 1. System setup and plot of the magnetic field lines around the reader.

The example can be considered representative of a wide class of modern commercial HF RF-ID systems [7]. In the figure, the reader unit is placed at the centre of a coordinate system ($x, y, z=0$), with the reader antenna lying on the x - y plane, and the z -axis orthogonal to the antenna. We define the coordinates of the tag as: x_2, y_2, z_2 (taken from its geometrical centre). Moreover, the tag can also be rotated along the tag shape-centred axis system x', y', z' (reference axis system of the tag) with angles θ, φ , and ρ respectively [2].

In an RF-ID system, the tag gains its needed energy to operate from an EM coupling with the reader unit, which creates a magnetic field at the system operating frequency. The tag's antenna couples with this field, leading to an induced voltage at its ends. The tag needs a minimal working voltage to power up its logic and to be able to transmit back the information stored in its memory, through a proper modulation. The EM coupling between the two antennas should be setup in such a way as to guarantee the minimal operative voltage to the tag element. The dependence of the operating conditions of the RF-ID system on the spatial coordinates and angles is essentially due to the physical properties of the EM coupling between the reader and the tag coil antennas. This is expressed by the coupling coefficient k associated to the two coils:

$$k = \frac{M}{\sqrt{L_1 \cdot L_2}}, \quad (1)$$

where M is the mutual inductance between the coils [8], while L_1 and L_2 are their self-inductances. Since the coils are different in size and shape, the two mutual inductances M_{12} and M_{21} assume different values; in fact, they are defined as:

$$M_{21} = \frac{\psi_{21}}{I_1} = \int_{A_2} \frac{B_2}{I_1} \partial A_2, \quad (2)$$

$$M_{12} = \frac{\psi_{12}}{I_2} = \int_{A_1} \frac{B_1}{I_2} \partial A_1, \quad (3)$$

where Ψ_{21} and Ψ_{12} are the partial magnetic fluxes generated by the reader (coil 1) and tag (coil 2), and enclosed by coil 2 and coil 1 respectively; they are described as closed integrals of the magnetic fluxes B_1 and B_2 around the coils area A_1 and A_2 . I_1 and I_2 are instead the currents flowing in the respective coils, whereas L_1 and L_2 are defined as:

$$L_i = \frac{\Psi_i}{I_i} = \frac{N_i \phi_i}{I_i} = \frac{N_i \cdot \mu \cdot H_i \cdot A_i}{I_i}, \quad i=1,2, \quad (4)$$

where Ψ_1 and Ψ_2 are the total fluxes through coil 1 and coil 2, due to the contribution of the single loops (N_1 and N_2) with the magnetic fluxes $\phi_1 = B_1 \cdot A_1$ and $\phi_2 = B_2 \cdot A_2$ [8]. $B_1 = \mu H_1$ and $B_2 = \mu H_2$ are magnetic flux densities, which depend on the magnetic permeability μ of the background material and on the magnetic fields H_1 and H_2 .

As can be seen in Fig. 1, the field lines bend more and more as z increases. Consequently, the component of the flux lines normal to the tag coil's plane decreases, leading to a less efficient coupling and a reduced induced voltage. A reduction of the coupled flux also arises upon the varying of the tag rotation around its center, *i.e.* upon the varying of the angles θ and φ . This description is clearly valid for the case of tag placed in front of the reader coil. But moving to the sides of the coil, and keeping the tag on the x', y' plane, the coils will again couple perfectly, since the flux lines will be normal again to the tag's coil antenna. In the side regions of the reader coil, the situation is therefore similar to the one that can be found in the front.

All of these positioning issues for the tag coupling are summarized in Fig. 2, where the best coupling areas around the reader antenna are represented [7]. In the sketch, the shaded areas represent the coupling regions with the tag parallel to the reader, while the blue line encloses the region of coupling with the tag orthogonal to the reader. In a 3D view, the areas become lobes, describing the coupling in the space around the reader coil.

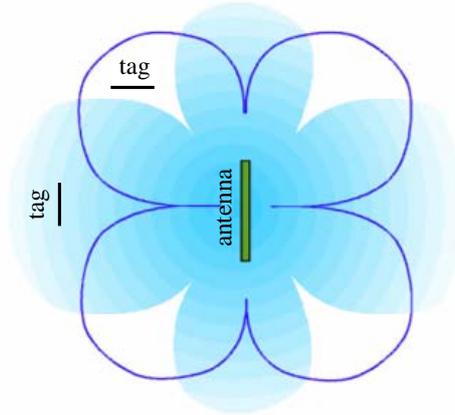


Figure 2. Reader coupling areas, depending on the tag orientation.

III. Modelling of the system

In this section, an efficient approach is proposed to model and evaluate the behaviour of an RF-ID system similar to that considered in the example of Fig. 1.

A. 3D Modelling and Meshing Issues

The reading range of an RF-ID system can be modelled by using the Finite Integration Method (FI-Method). The method requires the computational domain to be covered by a mesh. This step is critical, since simulation and result accuracy depend on the correct meshing setup and on the parameters chosen.

In the deployed EM CAD environment (CST design environment [9]), two meshing techniques are available: hexahedral and tetrahedral meshing. The former is the default technique, which subdivides the space and structure into cubic cells. Such a technique presents some problems whenever only some specific portions of the item to be analysed need a high resolution analysis. In this case, many mesh

lines are generated to satisfy the meshing resolution in the portions of interest; this implies a dense cell subdivision also in the non interesting regions of the item, with a consequent and useless increase of meshing complexity. However, if the size of the analysed feature is comparable to the meshing resolution, the entire cubic mesh cell will be filled with the same material. In the worst case, this will produce a short circuit in the structure, since the tag coil loops are so close to each other. The latter technique, based on tetrahedral meshing, adopts a smarter technique to subdivide the system into domains on which performing the EM computation. The structure under test is meshed in tetrahedrons, allowing to better follow the objects shapes and achieve higher accuracy levels. In this way, a detailed analysis can be focused only to the parts of the analysed feature demanding for higher resolution, without spending resources for the other parts, for which a coarser meshing structure can be sufficient. The choice of the tetrahedral meshing is advantageous since it leads to reduce the simulation runs, admit a parameter sweep of the tag's coordinates, and evaluate the S-parameters in every position of the tag.

B. Magnetic field and S-parameters

Once defined the model, a simulation can be setup by placing ports at the ends of the coils and adding suitable electric (E) and magnetic (H) field monitor indices to check the distribution in space of the fields. As a simulator, the Frequency Domain Solver of CST is used [9], which solves the problem for a single frequency at a time. The solution comprises the field distribution as well as the S-parameters, $S_{1,1}$, $S_{1,2}$, $S_{2,1}$, $S_{2,2}$, where the subscripts 1 and 2 stand for the reader and tag port respectively. However, the important parameter to be monitored is $S_{2,1}$, which describes the coupling on the tag due to the excitation of the reader. The deployed CAD system is asked to perform the calculation of the S-parameters for every different position of the tag with respect to the reader.

The computation is performed at different positions of the tag along the axes x and z , from the origin (centre of the reader antenna) to a maximum distance of 1.2 m along x and 1.0 mm along z , with a step of 5 cm, and keeping the tag parallel to the reader (*i.e.* $\theta = \varphi = \rho = 0$). Therefore, a total of 525 different positions are analyzed and one simulation is run per each of them. It is also noted that the structure shows a certain symmetry, therefore some computations could be avoided exploiting an expected symmetry of the radiated EM fields. However, as a matter of fact, the presence of cables and the reader box degrade the symmetry of both structure and EM field, therefore, a separate computation is commonly due per each point of the considered grid.

IV. Simulation results

A number of simulations have been performed according to the suggestions to the notes given in Section III and considering the generic and real life example of Fig. 1.

A. S-parameters evaluation

A plot of the estimated values of $S_{2,1}$ parameter is shown in Fig. 3 on the x - z plane and for $y = 0$. It has been obtained by using the standard colour scale "jet colormap" of Matlab.

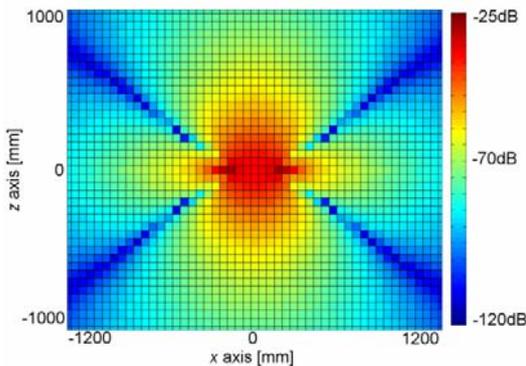


Figure 3. $S_{2,1}$ in dB over the x - z plane, for $y=0$.

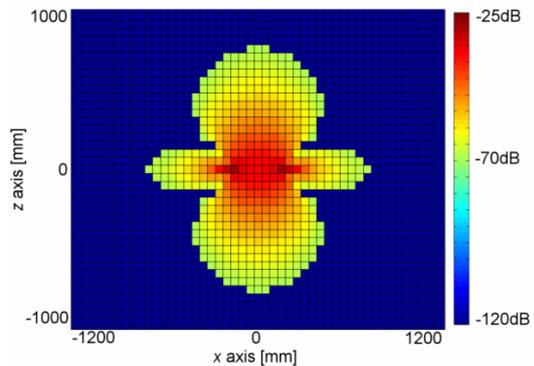


Figure 4. Filtered $S_{2,1}$ plot over the x - z plane, for $y = 0$ and $\varphi = 0^\circ$.

From the obtained values of $S_{2,1}$, the reading range associated to the RF-ID system can be derived. To this purpose, some information are needed about the minimum values of EM fields asked by the tag in order to feed the enlisted logic circuitry. For instance, one meaningful parameter typically declared by the RF-ID systems manufacturers is the maximum distance, z_{max} , between the reader and tag coils (with $y_2 = 0$ and $x_2 = 0$) beyond which the EM coupling is no more sufficient to guarantee the tag operation. In the analysed RF-ID system, for example, $z_{max} = 75$ cm. This means that the measured value of $S_{2,1}$, $S_{2,1}^*$, at the position with coordinates $x_2 = 0$, $y_2 = 0$ and $z_2 = 75$ cm is just the minimum $S_{2,1}$ value of the reading range that can be accepted (*i.e.* $S_{2,1}^* = 68.9$ dB in the analysed example). The reading range is thus defined as the 3D spatial region of points (x, y, z) in which $S_{2,1} \leq S_{2,1}^* = 68.9$ dB. Accordingly, the plot of Fig. 3 can be arranged and converted into the one of Fig. 4, which more clearly shows the obtained RF-ID system reading range.

B. 3D representation of the reading range

An investigation of the reading range has been performed in the space around the reader. This space has been subdivided for every coordinate combination $(x_2, y_2, \text{ and } z_2)$, with x_2 and y_2 ranging from -1.2 to 1.2 m and z_2 from -1 to 1 m, with steps of 5 cm length. The tag has been moved from a cell to another, and for each cell a different simulation has been executed. The tag has been kept parallel to the reader antenna. In order to perform a systematic simulation over the entire analyzed space, the resulting volume has subsequently been organized in slices. Each slice was a planar matrix-like arrangement of cubic cells, containing the values of $S_{2,1}$ in cells arranged in x - z planes. The total setup consisted of 49 slices, each made of 525 cells. A parameter sweep simulation for every sheet has then been performed. The resulting 3D slices have been wrapped with a texture skin exported from Matlab, giving a true colour scale. The obtained slices, stacked one upon another, permits to derive a final 3D representation of the reading range for all the possible positions of the tag, in the case of reader and tag coils parallels. From this 3D plot, reported in Fig. 5, some “dead-zones” nearby the reader can be noticed, in which the coupling is rather bad. These zones can be better analyzed through a two-dimensional representation on the x - z plane as shown in Fig. 4 and 6, respectively for the case of $\varphi = 0$ and 90° .

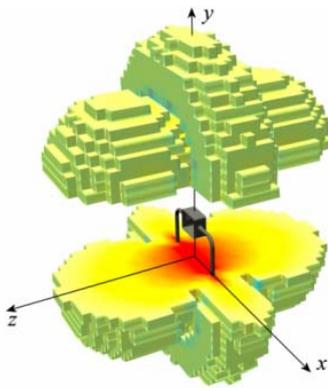


Figure 5. Cut-plane view of the 3D reading range plot.

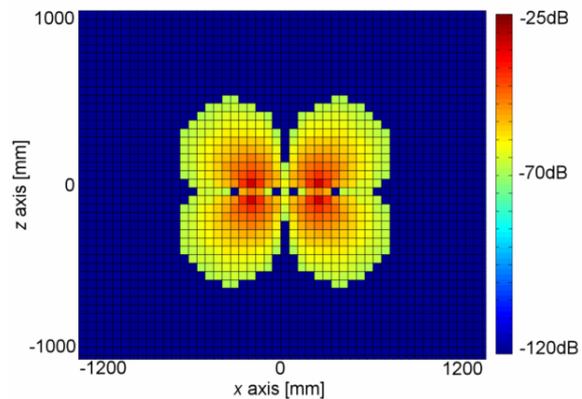


Figure 6. $S_{2,1}$ in dB over the x - z plane, for $y = 0$ and $\varphi = 90^\circ$.

C. Tag orientation

All the results presented in the previous sections only refer to the case of tag parallel to the reader antenna. Further interesting results can be achieved by considering the tag differently oriented with respect to the reader, *i.e.* by varying the angles θ and φ . In this latter case, a relevant change of the reading range is expected; in fact, the coupling between reader and tag coils depends on their mutual orientation. For instance, in the “dead-zones” found in the case of parallel coils, the coupling between reader and an orthogonal oriented tag is now very good. In fact, in these zones, the magnetic flux lines are parallel to the plane hosting the reader coil, hence they are orthogonal to the tag coil. For instance, the point of coordinates (7.5, 0, 3) cm is outside to the reader range in the case of $\varphi = 0$ (see fig. 4), and inside it with $\varphi = 90^\circ$.

V. Conclusions

An efficient numerical approach has been proposed in order to determine and analyze the reading range of an RF-ID system, in terms of its S-parameters. The main advantage of this technique lies in the numerical model, capable of analyzing the system also with non-ideal effects and keeping into account possible influences from the environment. This analysis allows a user to understand how the system works and behaves when some variables of the setup change (e.g. θ , φ , x_2 , y_2 , z_2). The behaviour of the physical system can thus be predicted, knowing in advance the situations to be avoided and the cases in which the setup is working correctly.

A future development of this work could revise the above defined model by introducing real-world non-idealities, thus understanding the influence on the RF-ID system of foreign objects or undesired interference as well as a multi-tag behaviour and coupling of tags close to metallic surfaces.

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