Calculation of the equivalente mutual impedance in complex HF RFID systems

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To cite this version :

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Abstract— **In this work the improvement of HF RFID detection is obtained by the addition of small resonator in the reader coil. In conventional RFID system, the link between the reader and the tag coils is the mutual inductance, the added resonator is magnetically coupled with the reader coil, and then the link is expressed by the mutual impedance. Theoretical calculation of the equivalent mutual impedance of such system is reported and validated by comparison with HFSS simulation and measures.**

Keywords— rfid;mutual impedance;HF

I.   INTRODUCTION

An inductively coupled RFID HF system is based on the magnetic coupling between the reader and the tag coils. In the case of weak coupling, the detection performance of the tag is fruitfully evaluated by the mutual inductance as a figure of merit [1][2][3][4]. A current challenge in HF RFID is to increase the surface and, if possible, the volume of detection by customizing the shape of the reader antenna [5][6][7]. More precisely, a way of improvement is studied and obtained by the addition of a small resonator coil. The addition of a resonator concentrates and modifies the vectorial distribution of the magnetic field generated by the reader, as it can be shown in Fig.1. Accordingly, optimal detection areas can appear.
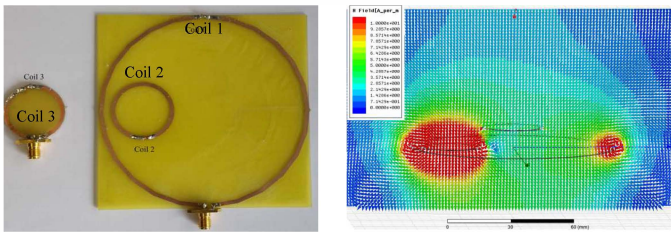

Fig. 1. Proposed structure and its generate magnetic field

In the following section of this paper, we investigate the formula defining equivalent mutual impedance between the dual-coils structure and the tag coil, and validate these relations, in section III, by simulations under HFSS (High Frequency Structure Simulator) and measurements using a Vectorial Network Analyzer.

II.   ANALYTICAL CALCULATION OF THE EQUIVALENT IMPEDANCE MATRIX

Fig.2 is the electrical model of the system composed by the dual-coils reader and the tag coil, where. L_1=0.3 uH, L_2= 0.058 uH and L_3=0.058 uH are respectively the self-inductances of coils 1, 2 and 3. r_1=0.1Ω, r_2=0.06Ω and r_3=0.06 Ω are their internal resistances. C_1=0.45 nF, C_2=2.32 nF and C_3=2.32 nF are the series tuning capacitors at 13.56 MHz.

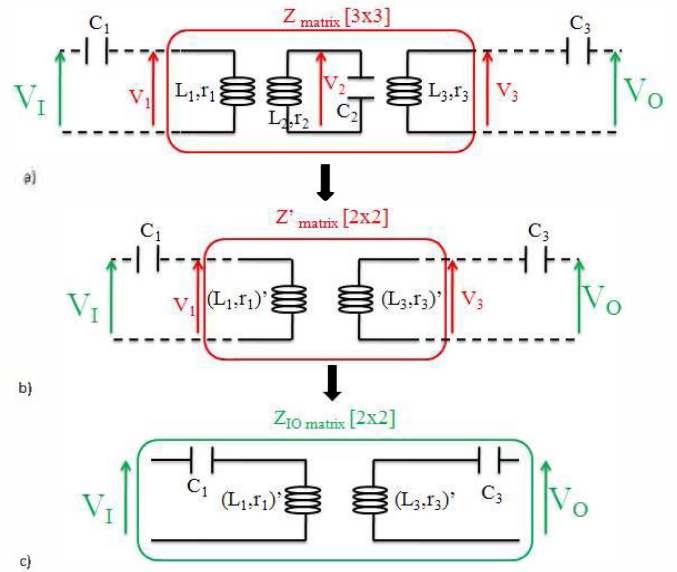Fig. 2. Electrical equivalent models (a to c) of inductively coupled dual-coils reader/tag system
a) initial equivalent model corresponding to matrix Z
b) simplified Z' matrix integrating the coil resonator
c) experimental Z_{IO} matrix obtained with VNA

The voltages V_1, V_2 and V_3 in the circuit satisfy the following relations (1), with $M_{ij}=M_{ji}$ being the mutual inductances between coils 1, 2, 3, (1<i,j<3))

$$\begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} \tag{1}$$

$$= \begin{bmatrix} r_1 + j\omega L_1 & j\omega M_{12} & j\omega M_{13} \\ j\omega M_{21} & r_2 + j\omega L_2 & j\omega M_{23} \\ j\omega M_{31} & j\omega M_{32} & r_3 + j\omega L_3 \end{bmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix}$$

In simulation, each coil is fed by a lumped port, so we have matrix results with [3x3] data dimensions, but in measurements we used only the two ports of the vector network analyzer (VNA): one port for feeding the reader dual-coils structure (coil 1 with the influence of coil 2 loaded by C_2), and the second port used for feeding the tag coil (coil 3). Consequently, we have experimental Z_{IO} matrix results with [2x2] data dimensions. Using analytical formulas, we can develop the equivalent matrix of the system (see Fig.2).

We consider the expressions of V_1 and V_3 mentioned in (1) with:

$$V_2 = \frac{j I_2}{C_2 \omega} \tag{2}$$

The expression of current I_2 in the resonator is given by (3):

$$I_2 = \frac{j\omega M_{12}}{\alpha} I_1 + \frac{j\omega M_{23}}{\alpha} I_3 \tag{3}$$

Where: $\alpha = \dfrac{j}{\omega C_2} - (j\omega L_2 + r_2)$

The equation's system becomes:

$$V_1 = (r_1 + j\omega L_1) I_1 + j\omega M_{13} I_3 + j\omega M_{12}$$
$$\left(\frac{j\omega M_{12}}{\alpha} I_1 + \frac{j\omega M_{23}}{\alpha} I_3 \right). \tag{4}$$
$$V_3 = j\omega M_{31} I_1 + (r_3 + j\omega L_3) I_3 + j\omega M_{32}$$
$$\left(\frac{j\omega M_{12}}{\alpha} I_1 + \frac{j\omega M_{23}}{\alpha} I_3 \right).$$

From these equations, the Z' matrix elements are equal to:

$$Z_{11}' = r_1 - \frac{\omega^2 M_{21}^2}{\alpha} + j\omega L_1$$

$$Z_{13}' = j\omega M_{13} - \frac{\omega^2 M_{12} M_{23}}{\alpha} \tag{5}$$

$$Z_{31}' = j\omega M_{31} - \frac{\omega^2 M_{32} M_{12}}{\alpha}$$

$$Z_{33}' = r_3 - \frac{\omega^2 M_{23}^2}{\alpha} + j\omega L_3$$

In the following step of the calculus, the capacitors C_1 and C_3 are inserted in order to find the final Z_{IO}-matrix of the entire

system: a conversion from impedance matrix to chain matrix is used.

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = (\beta(1)) \begin{pmatrix} A' & B' \\ C' & D' \end{pmatrix} (\beta(3)) \tag{6}$$

Where $(\beta(1))$ and $(\beta(3))$ are the chain matrix of both capacitors C_1 and C_3.

$$(\beta(i)) = \begin{pmatrix} 1 & Z_{C_i} \\ 0 & 1 \end{pmatrix} \tag{7}$$

The final Z_{IO} matrix, considering the capacitors C_1 and C_3, has the following terms:

$$Z_{ii} = r_1 - \frac{\omega^2 M_{21}^2}{\alpha} + j\omega L_1 + Z_{C_1}$$

$$Z_{io} = j\omega M_{13} - \frac{\omega^2 M_{12} M_{23}}{\alpha} \tag{8}$$

$$Z_{oi} = j\omega M_{31} - \frac{\omega^2 M_{32} M_{12}}{\alpha}$$

$$Z_{oo} = r_3 - \frac{\omega^2 M_{23}^2}{\alpha} + j\omega L_3 + Z_{C_3}$$

When we develop, the parameters of the Z_{IO} matrix can be expressed as:

$$Z_{ii} = j\omega \left(L_1 - \frac{1}{C_1 \omega^2} + \omega M_{21}^2 \gamma \right) + \omega^2 M_{21}^2 \delta + r_1.$$

$$Z_{io} = j\omega (M_{31} + \omega M_{12} M_{23} \gamma) + \omega^2 M_{12} M_{23} \delta$$

$$Z_{oi} = j\omega (M_{13} + \omega M_{32} M_{21} \gamma) + \omega^2 M_{32} M_{21} \delta \tag{9}$$

$$Z_{oo} = j\omega \left(L_3 - \frac{1}{C_3 \omega^2} + \omega M_{31}^2 \gamma \right) + \omega^2 M_{31}^2 \delta + r_3$$

With

$$\gamma = \frac{\dfrac{1}{C_2 \omega} - \omega L_2}{\left(\dfrac{1}{C_2 \omega} - \omega L_2 \right)^2 + r_2}$$

$$\delta = \frac{r_2}{\left(\dfrac{1}{C_2 \omega} - \omega L_2 \right)^2 + r_2}$$

It can be seen in equations (9) that the resonator influences all terms of the Z-matrix. In this study, we are interested in the equivalent mutual impedance parameters (Zio or Zoi): the improvement of the RFID detection is done by the maximization of the module of these parameters. We use in the

following sections the terms of equivalent mutual inductance and equivalent mutual resistance for, respectively, the imaginary part divided by ω and the real part of the equivalent impedance parameter. Their calculated expressions are given from equation 3:

$$M_{eq} = M_{13} + \omega M_{12} M_{23} \gamma$$
$$R_{eq} = \omega^2 M_{13} M_{23} \delta \tag{10}$$

III. VALIDATION OF THE CALCULATED EQUIVALENT MUTUAL IMPEDANCE

As the addition of a coil resonator on the surface of the reader is studied by calculation and simulation, we developed a specific measurement set-up to evaluate the equivalent mutual impedance improvement, in function of the tag orientation and a lateral misalignment. This measurement-setup (Fig.3) is ensuring lateral variations between the coils, using graduate millimeter scale to read accurately the position of the tag relative to the reader one.
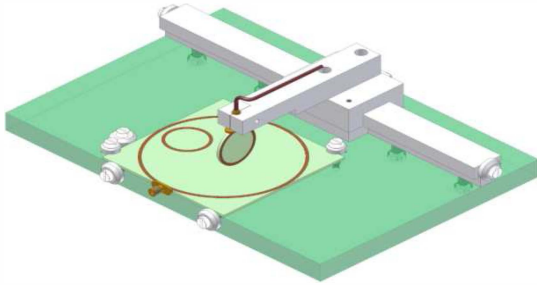

Fig. 3. Misalignment measurement-setup system fabricated

For tag misalignment (-50 mm<y<50mm), the equivalent mutual impedance is evaluated according to the calculated expression (equation 10), and compared to the simulated and measured results in both parallel and perpendicular configuration (Fig.4).
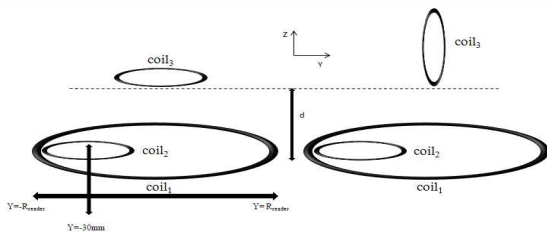

Fig. 4. Parallel (left side) and perpendicular (right side) configurations

The addition of the resonator can increase the equivalent mutual inductance and mutual resistance respectively by 10 nH (from 11nH to 21nH) and 1.1 Ω (from 0 Ω to 1.1 Ω) above the resonator in parallel configuration (the comparison with and without resonator corresponds respectively to -50 mm<y<0mm and 0 mm<y<50mm where y=-30mm is the center of the resonator and y=±50mm are the edges of the reader coil) (Fig.5). However, in perpendicular configuration, the equivalent mutual inductance and the equivalent mutual resistance are improved respectively by 1.5 nH (from 3.5 nH to 4.5 nH) and 0.11 Ω (from 0 Ω to 1.1 Ω).
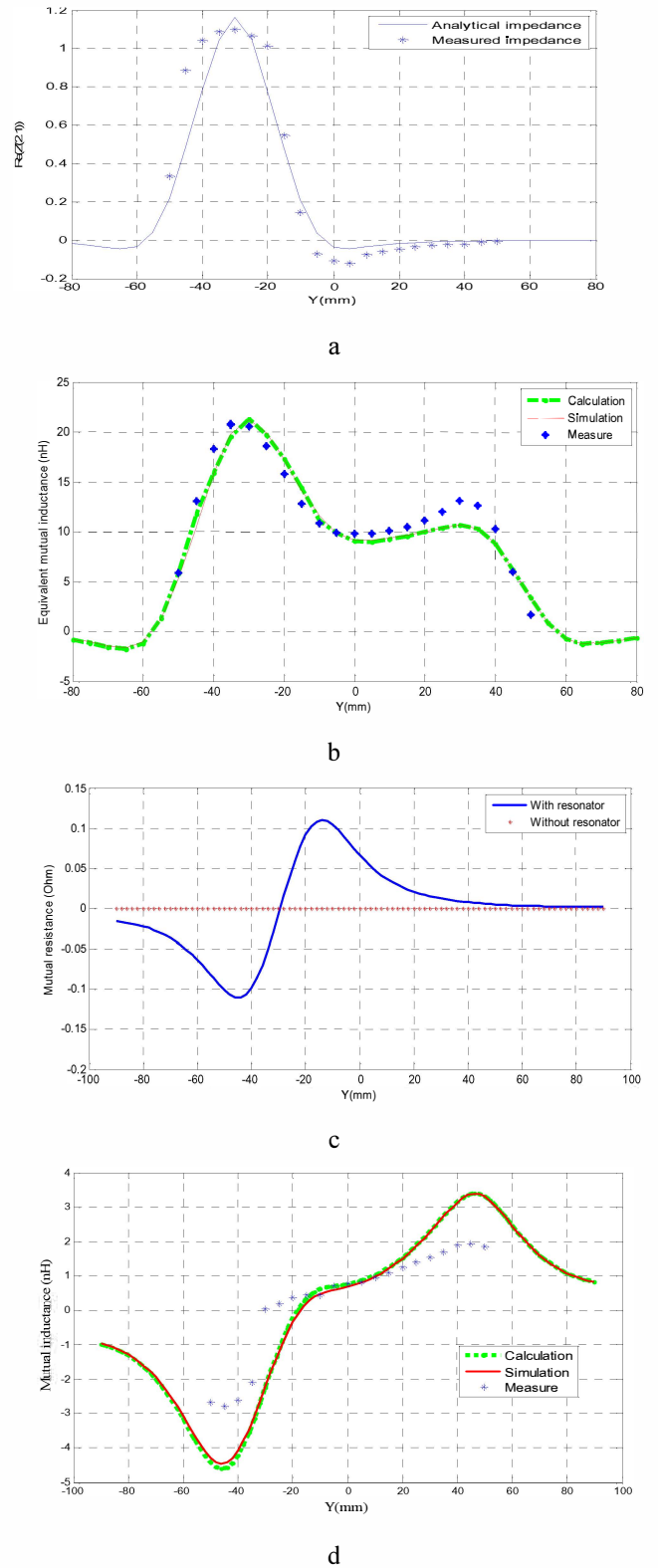

a

b

c

d

Fig.5. Equivalent mutual inductance (b, c) and equivalent mutual resistance in parallel and perpendicular configuration

The positions of the maxima of the equivalent mutual inductance and mutual resistance are always on above the resonator (y=-30 mm).

The calculated mutual impedance (real and imaginary parts) is confirmed by comparison to simulation and measures of the structure in both parallel and perpendicular configuration. Because of the few values of the mutual resistance in the case of perpendicular configuration, only calculation results are presented.

IV. Conclusion

Analytical calculation of the equivalent impedance matrix of complex HF RFID system is reported in this article. The principle of adding resonators in the reader coil modifies the distribution of the magnetic field, and can then increase detection volume and surface. The performances of RFID systems are evaluated by the mutual inductance, the added resonator changed this operation. New formulas of equivalent mutual impedance must be defined with the presence of resonator. These formulas are presented in this article and validated by simulations and measures of a dual-coil reader antenna. In future works, the equivalent self impedance parameters will be studied for evaluating the degradation of RFID performances by the added resonators. The degradation concerns the shift frequency in the reader and the tag coils.

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