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Modeling of a metamaterial in the FEA of a contactless transcutaneous energy transfer device

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Abstract— Metamaterials are difficult to deal with in computational electromagnetic modelling, e.g. finite element analysis. The reason is the prohibitive discretization refinement needed to account for their actual electromagnetic field distribution profile, within the frequency range used in contactless energy transfer devices. We propose an approach to simplify the modeling of a metamaterial in finite element simulations and present an analysis of its impact in the evaluation of the magnetic field distribution in the vicinity of the metamaterial.

Keywords—metamaterial; computational electromagnetics; finite element analysis; transcutaneous energy transfer; contactless energy transmission

I. INTRODUCTION

Metamaterials (MM) could be defined as artificial materials having physical properties not encountered in the nature. In the context of Electromagnetism, they are known as left-handed media, since, theoretically, they behave as homogeneous, hypothetic media with negative permittivity and/or negative permeability at given frequencies.

Metamaterials were first described theoretically by Veselago in 1967 [1]. In 1999 John Pendry was the first one to design a MM using split ring resonators [2]. These are copper circuits (thin trails) printed on a fiberglass slab.

One of the promising, recent applications of MMs [3] [4] is to enhance the inductive coupling of WPT (Wireless Power Transfer) systems, and hence improving its efficiency. In [4] the authors achieved about 400% voltage gain in the receiver by using a MM, in the frequency range of tens of MHz.

Placed between the transmitter and the receiver coils of a WPT system, which are usually located far apart each other, the MM acts as a bridge, improving the inductive coupling.

In this work, the interest in modeling the MM is to evaluate its effects in the performance of a Transcutaneous Energy Transfer (TET) system [5], aimed at transmitting energy to artificial organs implanted in humans, like ventricular assist devices (VAD) [6].

In this application, TET devices operate in the frequency range of hundreds of kHz. In this case, the MM is introduced to compensate, not the impact of the distance between the two coils, but the effect of both skin and fat, which act as a barrier.

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FEA is used to computationally simulate the TET system, in order to evaluate its efficiency. Due to the presence of the MM, the TET system loses its 2D symmetry, and a 3D modeling is necessary. However, the mesh density in 3D, needed to account for all the MM features (large aspect ratio of copper track width and slab dimensions, skin and proximity effects, losses), yields an impracticable computational cost.

Therefore, we intend to use a thin wire model to represent the MM in the 3D domain. In the next sessions we investigate the suitability of this approach, regarding the impact of neglecting skin and proximity effects in the MM.

II. METAMATERIALS

The unusual properties of the MMs are due to their structures rather than chemical composition [4].

The MM is a periodic arrangement of scattered elements that can be synthesized and considered as homogeneous, if the unit cell dimension is smaller than the guided wavelengths. Fig. 1 shows examples of MMs tested in [3]. These are copper tracks printed on fiberglass with a specific geometry. Furthermore, for MMs formed by repeated motifs printed in a slab, and when the slab dimensions are large compared to the dimension of one motif (as in Fig. 1a), it is possible to analyze its properties by studying a single unit cell [4].

Capacitors are connected in series with these circuits in order to form a RLC circuit, which resonate at a given frequency. Those configurations are tested in [3] and [5], and that of Fig. 1b will be the one chosen for our preliminary analysis, due to its lower geometrical complexity. Nevertheless, our aim is to devise a more compact model to enable the simulation of the more complex set of Fig. 1a in the future.

III. 3D FINITE ELEMENT MODELING

A 3D model of a TET device with a MM, like the one in

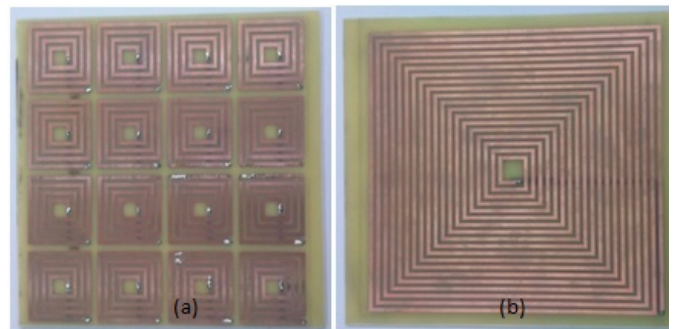


Fig. 1. Some configurations of printed circuit boards used as metamaterials [1]: (a) periodic structure with repeated patterns; (b) single square spiral.

Fig. 1b, placed between the transmitter and the receiver coils of the system under test, is shown in Fig. 2. It is evident in this figure that the 2D model used in the FE simulations in [6] and [8] can no longer be used due the presence of the square-spiral MM, as it destroys the cylindrical symmetry of the TET system, even with no coil misalignment.

By using a “shell region” approach in the 3D FE model, the burden of domain discretization could be slightly alleviated, thanks to the flat geometry of the MM [5]. However, since the printed copper stripes are very slim and the operating frequencies are high, a strong skin effect, as well as proximity effect, arises in the MM.

The attempt to follow the recommended rule-of-thumb of employing at least 2 layers of second-order finite elements along the skin depth leads to an unfeasible number of mesh elements in the finite element domain of the MM, even with the shell element resource.

In order to make this 3D finite element modeling feasible, we need a more compact model for the MM. A convenient approach would be a thin wire representation for the copper strips.

In order to verify the thin wire approximation, in the next sessions we present an analysis of its impact on the solution, following a procedure similar as in [7], applied to a printed-circuit copper loop. In [7], the behavior of a printed circuit loop is studied both as the source of field and as a sensor. It is shown that in the frequency range of 20 kHz to 2 MHz (the scope of this work), a copper-loop printed circuit can be likened to a thin wire loop.

IV. THIN WIRE MODEL OF THE METAMATERIAL

To verify the validity of the thin wire approach, we tried to perform two reduced 3D FE simulations, both with the square-spiral MM alone: (i) in the first one, the copper stripes are finely meshed with the recommended mesh density along the skin depth to account for the skin effect; this would be our “reference”, complete solution; (ii) in the second, a “reduced model” are adopted, where the stripes are replaced by thin

wires

The aim was to compare the two solutions and evaluate the relative error in the magnetic field distribution in the vicinity of the MM, namely, along a conveniently chosen path. Unfortunately, despite the reduced 3D domain adopted, the first, “complete” model also gave rise to an unfeasible mesh size.

Therefore, the only alternative left is trying to validate the thin-wire approach by means of a 2D FEA, as in [7]. Nevertheless, the square-spiral MM of Fig. 2 does not exhibit any 2D symmetry (neither planar nor cylindrical).

We need to find an alternative configuration of MM which possesses axial symmetry, whereas keeping the main features of the square spiral.

Then, we chose, as a test MM, a pattern composed of a 16-turn circular spiral strip, with dimensions equivalent to the square-spiral MM of Fig. 2. The next session presents an outline of the numerical experiments devised to evaluate the thin-wire approximation.

A. Outline of the test cases for the 2D simulations

In order to analyze the impact of the thin wire approach, several 2D simulations were carried out. In all cases, the values of magnetic flux density are computed along a path in the close vicinity of the MM. These values are then compared with the theoretical thin wire values.

Two set of simulations were performed: (a) firstly, by changing the number of turns of the spiral, keeping the frequency fixed; (b) then, with a fixed number of turns, the frequency is varied. The Altair Flux ® commercial software was used in this work for the finite element simulations, with a mesh of second-order elements.

Fig. 3 shows the 2D axisymmetric FE model. The tiny rectangles represent the several turns of the circular MM. The spiral path was modeled by concentric copper loops spaced 1 mm and connected in series. Its finite element discretization is depicted in Fig. 4, where the number of elements in the skin depth was chosen for the highest frequency in the range of

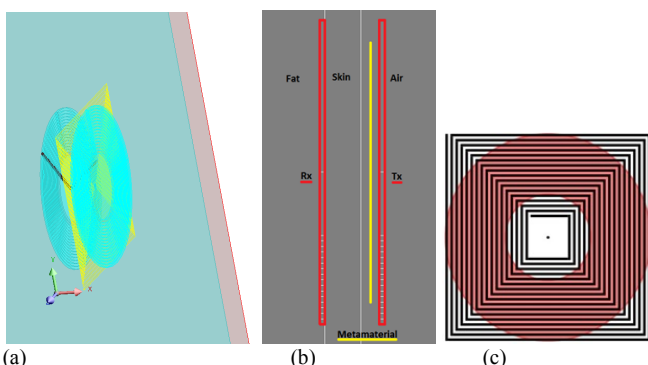


Fig. 2. 3D model (a) for the FE simulation of the TET system with the metamaterial placed between the TET coils and outside the human body, and its side view (b). Top view of TET coil and the square-spiral metamaterial (c).

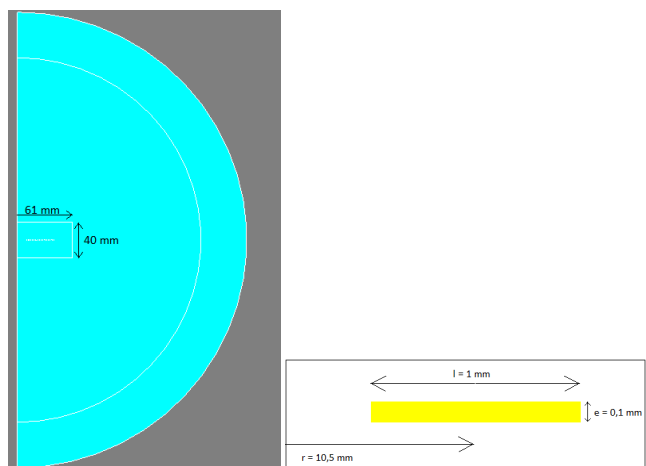


Fig. 3. Axisymmetric 2D FE model of the domain, representing the cross-sectional view of the circular copper loop (left) and detail of one stripe with dimensions (right).

interest, 1 MHz.

For the FE magnetodynamic simulations, the spiral was fed by a current source of 1 A rms, with all turns connected in series.

V. SIMULATION RESULTS

A. Single copper loop at several frequencies

In order to verify the validity of the 1D model, we start with a domain composed of a single-turn (one loop) MM, the same configuration as in [7].

The aim is to compute the magnetic flux density, B , in a given path for this configuration, which was very finely meshed, so as to be taken as the reference solution. Then, a second simulation is performed with the copper stripe replaced by a 1D element, i.e., a point region in the 2D domain, placed in the middle of the stripe. Finally, the preceding numerical results are compared with the classical analytical solution of B produced by a magnetic dipole.

These simulations were carried out for a frequency range of 80 kHz to 1 MHz, values that are commonly used for TETs in VAD drives [8].

The results of the simulations are presented in Fig. 5, where the left picture illustrates the path along with the normal component of the magnetic flux density was computed.

Fig. 5b shows the flux density for all the aforementioned scenarios. These results confirm those obtained in [7], i. e., despite the strong skin effect observed in the copper loop, the thin-wire approach has very little effects the field distribution from a given distance from the MM.

Table I summarizes these computational results, showing the relative mean-square error in the magnetic flux density computed along the yellow path of Fig 5, as follows:

$$\varepsilon = \sqrt{\frac{\sum (B_S - B_T)^2}{\sum B_T^2}}$$

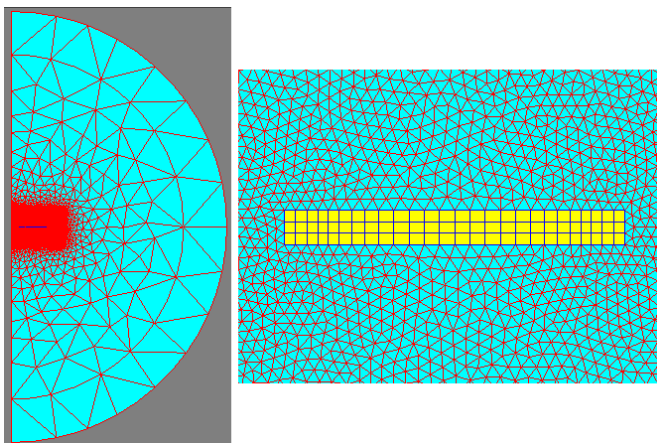


Fig. 5. Finite element mesh of domain in Fig. 3 (full domain at left; detail of one copper strip at right).

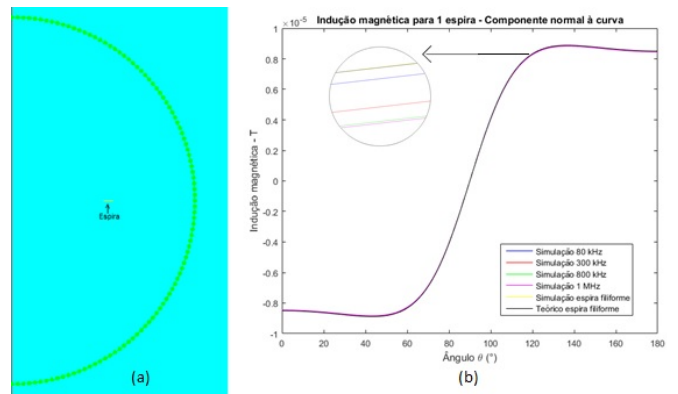


Fig. 4. (a) 2D FE model of the single-turn metamaterial showing the path (half circle) for field computation. (b) Plot of the magnitude of normal component of the magnetic flux density along the half circular path of (a). The detail shows an enlarged excerpt of the curves.

where B_T is the theoretical value of the flux density and B_S is the simulated one. The errors observed in Table I, for the whole analyzed frequency range, are negligibly low. All of them are far below 1%, despite a slight increase as the frequency rises.

TABLE I.
RELATIVE MEAN-SQUARE ERROR (%) ON THE COMPUTATION OF THE NORMAL COMPONENT OF MAGNETIC-FLUX DENSITY FOR SEVERAL FREQUENCIES, ALONG THE PATH DEPICTED IN FIG. 6, FOR A PRINTED-CIRCUIT LOOP.

COMPARISON OF 2D FINITE ELEMENT SIMULATIONS OF THE SINGLE-TURN COPPER STRIPE METAMATERIAL (BOTH COMPLETE AND 1D MODEL) WITH THE THEORETICAL THIN-WIRE RESULT

ε (%)	Thin wire	Complete model			
		80 kHz	300 kHz	800 kHz	1 MHz
	0,0125	0,1530	0,3861	0,5209	0,5385

B. Effect of the number of turns

Besides the pronounced skin effect that arises in the copper stripes of the MM at high frequencies, a larger number of turns also affect its current distribution, due to the proximity effect. These phenomena can be clearly observed in the studied configurations, as shown in Fig. 6. Therefore, it is necessary to verify if the error committed by the thin-wire approximation remains acceptable, as in the single-turn case. The behavior of the field as the number of turns increased was verified in two parallel, straight paths, placed 2.5 mm and 12.5 mm from the plane of the MM. Fig. 7 shows a comparison of the flux densities generated by 1 and 16 turns.

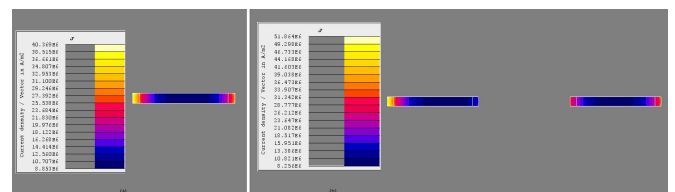


Fig. 6. Color shades of magnitude of the current density in the copper stripes at 800 kHz: (a) 1 turn (showing the skin effect); (b) 2 turns (both skin and proximity effects).

Once more, the computed field values were compared to the analytical calculation, in which each copper stripe was replaced by a thin wire. The mean-square error (ϵ) was calculated as previously. Table II shows the results obtained for 2, 4, 8 and 16 turns at the frequency of 800 kHz.

TABLE II. EFFECT OF NUMBER OF TURNS RELATIVE MEAN-SQUARE ERROR (%) ON THE COMPUTATION OF THE MAGNITUDE OF NORMAL MAGNETIC FLUX DENSITY, COMPUTED FOR SEVERAL NUMBER OF TURNS, ON PATHS PARALLEL TO THE METAMATERIAL (MM) AND PLACED AT DISTANCES 2.5 AND 12.5 MM. COMPARISON OF 2D FINITE ELEMENT SIMULATIONS AT 800 KHz OF THE SINGLE-TURN COPPER STRIPE METAMATERIAL (BOTH COMPLETE AND 1D MODEL) WITH THE THEORETICAL THIN-WIRE RESULT

d^a	2.5				12.5				
	turns	2	4	8	16	2	4	8	16
ϵ (%)	1,924	2,203	2,029	1,705	0,620	0,794	0,864	0,774	

^a Distance (mm) from MM.

The errors did not exceed 3% with increased number of turns. The maximum error for a distance of 2.5 mm was 2.2% with 4 turns. For a distance of 12.5 mm and 8 turns, the error was 0.86%.

C. Effect of increasing frequency

The increase in frequency affects the current distribution in the conductors. The current density is concentrated in the periphery of the stripes due to the skin effect and the field distribution is also modified, as shown in Fig. 7. Tables III-IV show the mean-square error at several frequencies for 1 and 16 turns, respectively.

TABLE III. EFFECT OF FREQUENCY (SINGLE TURN) ROOT-MEAN-SQUARE ERROR IN MAGNETIC FLUX DENSITY OF A COPPER STRIPE

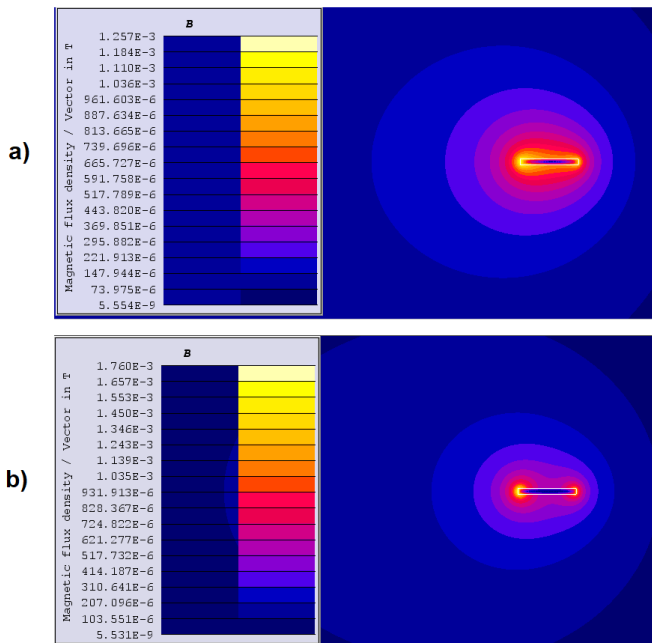


Fig. 7. Magnitude of magnetic flux density generated by a loop at frequencies (a) 80 kHz and (b) 1 MHz.

LOOP AT DIFFERENT DISTANCES - COMPARISON BETWEEN FE SIMULATION AND THEORETICAL VALUE FOR THIN WIRE APPROACH.

d^b	2.5				12.5				
	kHz	80	300	800	1000	80	300	800	1000
ϵ (%)	0,803	1,068	1,313	1,353	0,170	0,332	0,433	0,443	

^b Distance (mm) from MM.

TABLE IV. EFFECT OF FREQUENCY (16 TURNS) ROOT-MEAN-SQUARE ERROR MAGNETIC FLUX DENSITY AT DIFFERENT DISTANCES OF THE SPIRAL - COMPARISON BETWEEN FE SIMULATION AND THEORETICAL VALUE FOR THIN WIRE APPROACH.

d^c	2.5				12.5				
	kHz	80	300	800	1000	80	300	800	1000
ϵ (%)	0,263	1,146	1,705	1,781	0,116	0,518	0,774	0,810	

^c Distance (mm) from MM.

In all situations the error of the thin wire approximation increases with frequency, but remains below 2% for the frequency band of interest.

CONCLUSION

In order to study the impact of using a metamaterial in the performance of a TET system, the FEA can be a valuable tool, but it must be carried out in 3D. However, with the available current computational resources, including a MM in the 3D domain with its actual dimensions is not feasible, and a reduced model must be devised. In this work, we try to show that a thin wire approach can be a viable alternative.

To evaluate the suitability of the thin wire approach we presented an analysis of the error of this approximation with respect to the complete, full model of the MM. This analysis is performed with the aid of 2D FE simulations, since a 3D mesh of the actual MM led to an impractical number of elements. We then chose a simplified model of the MM, namely, a round spiral, to enable a 2D simulation. In these first experiments the MM was simulated as active source of fields (inductor), and the impact of the number of turns, as well as operating frequency was verified.

In all test cases the error in replacing the copper stripe by a thin wire did not exceed 3% in a close vicinity of the MM, showing that this approach can be used in the finite element analysis. It is worth mentioning that we are assuming that the results obtained for a circular spiral can be extended to the case of the square spiral, but this hypothesis needs to be verified, what will be done in the extended version of this work. Moreover, additional validation experiments are in course, but not yet fully documented at the moment of the paper submission. These are: (i) testing the MM as a passive, induced circuit, although this analysis was already been reported in [7] as well, with no significant change in the errors; (ii) instead of a single, using two thin wires in parallel, placed at the two edges of the copper stripe; (iii) perform the 3D simulation with the thin wire approach, both single- and two wire, and for both circular- and square-spiral MMs.

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