The Electromagnetic Field and Radio Frequency Circuit Co-simulation for Magnetic Resonance Imaging Radio Frequency Coils

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Electromagnetic (EM) field simulation plays a key role in the design of magnetic resonance imaging (MRI) radio frequency (RF) coils. However, the scattering parameter calculation need to be repeated many times in simulation using finite integral technology to achieve optimal results. It makes the efficiency low in the process of RF coil tuning and matching. In order to improve simulation efficiency, a method combining the finite integral technology simulation and circuit simulation was employed in this paper. It can quickly determine the required capacitance and EM field resulting in magnetic resonance. Its performance is validated by a comparison study with the conventional simulation approach.

Index Terms—**Magnetic resonance imaging, radio frequency coil, electromagnetic field, simulation.**

I. INTRODUCTION

THE MAGNETIC resonance imaging (MRI) is a primary imaging modality used in current biomedical research and clinical applications. In order to obtain high quality MRI images, homogeneous magnetic field of is needed [1]. In design of multi-channel radio frequency (RF) array coils, the simulation is also an effective method to study the electromagnetic interactions between the load and RF coils [2]. Due to the limitation of the current numerical algorithms, simulation of RF coils is usually time-consuming. To enhance simulation efficiency, a method combining the electromagnetic field (EM) data and circuit simulation was employed in this paper.

II. THEORY

A RF coil simulation strategy which can dramatically shorten the computation time is demonstrated in this paper. The field circuit co-simulation approach is applied to the RF coil tuning simulation [3]-[4]. First replace the lump elements into the discrete excitation port in the conventional simulation, calculate the initial value of the EM field distribution of each discrete excitation port and build the circuit in the RF circuit simulation [5]. Secondly, the RF coils are tuned and matched according to the circuit theory and each port electromotive force and circuit parameters can be exported. Finally, the results of circuit simulation and the individual prototype EM field are combined to get the distribution of electromagnetic field. It is more efficient than conventional simulation by tuning the lumped element in ciruit simulation instead of in field simulation. Once the RF coil is tuned and matched, the EM field and specific energy absorption (SAR) are obtained. The workflows of the two simulation are shown in Fig. 1.

III. METHODS

The commercial CST software (Computer Simulation Technology, Darmstadt, Germany) is used to validate the proposed simulation method in this study. As an example, the 3-channel phased array coil is used [6], which consists of 3 loops with 40 mm in radius and 3 mm in conductor width. The coil is modeled in microwave studio (MWS) and the conductor of the coil is set as copper. The cubic phantom with the dimensions of $200 \times 60 \times 80$ mm^3 is placed 5 mm from the top of the RF coil model. The material property of phantom is set with permittivity $\varepsilon_r = 74$ and permeability $\mu_r = 0.99$. In the conventional simulation procedure, the ports and capacitors are arranged at the gaps of the RF coil model in traditional fashion as shown in Fig. 2 (A). The red and blue components in Fig. 2 (A) denote ports and capacitors respectively. In the proposed simulation procedure, all the lumped elements are replaced by the ports with impedance 50 Ω impedance as shown in Fig. 2(B). We use time domain solver and the steady state accuracy limit is set to -30 dB. All the directions are set to open boundary. Bandwidth is 50 MHz ~ 200 MHz.
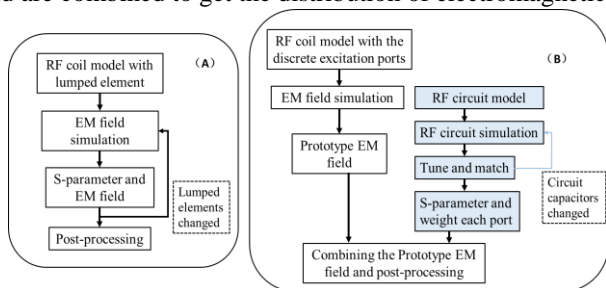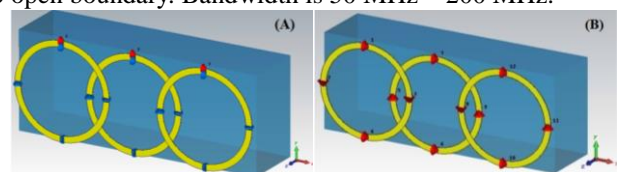

Fig. 2. The RF coil model for EM field simulation for conventional (A) and co-simulation (B).

The RF coil is tuned to 123.2 MHz by changing the capacitence of the capacitors. In conventional simulation, coils are tuned by changing the lumped elements and all simulations are performed in MWS to obtain the EM field and SAR. In the co-simulation, coils are tuned by changing the capacitance in design studio (DS) and combining the individual prototype EM

Fig. 1. The two simulation workflows for 3-channel RF coil model simulation.(A) Conventional simulation (B) Co-simulation

field based on the tuned data of the external ports to obtained the EM field and SAR [7]. The EM field and the SAR data of the X-Y plane of the two method are exported and compared to validate the accuracy of the proposed method.The total time required for the two simulations are defined respectively as

$$t_{MWS} = t_{mws\text{-}ch} \cdot n \cdot m \qquad (1)$$
$$t_{co\text{-}sim} = t_{co\text{-}p} \cdot n_e \cdot n + t_{ds} \cdot m \qquad (2)$$

in which the t_{MWS} and $t_{mws\text{-}ch}$ denote the total and individual channel simulation time in conventional procedure respectively. $t_{co\text{-}sim}$, $t_{co\text{-}p}$ represent the total time and and the time for individual port of prototype EM field simulation of the proposed method respectively. t_{ds} is the time in circuit simulation. n is the number of channels, n_e is the number of lumped element, m is the number of simulations.

IV. RESULTS

In this model, $n = 3$ and $n_e = 4$. There take 6 simulations to achieve the capacitance for coil tuning. The total time for the simulations are compared and shown in Table I. The proposed co-simulation method saves about 79.85% of the time.

TABLE I
The detailed data of two methods

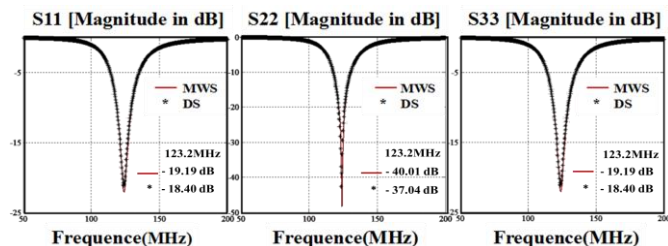|	m	t_{ds} (min)	$t_{co\text{-}p}$ (min)	Time for each channel of once simulation (min)	Total time (min)
Conventional simulation	6	N/A	N/A	$t_{mws\text{-}ch}$=10.78	194.04
Co-simulation	6	0.25	3.4	$t_{co\text{-}p} \cdot n_e$=13.6	42.3

Fig. 3. The S-Parameter for conventional simulation and co-simulation

TABLE II
Field distribution comparison of two methods

	conventional simulation	co-simulation	Deviation(%)
Mean of e-field data (V/m)	8.782	8.927	1.65%
Mean of h-field data (A/m)	0.743	0.719	3.23%
Mean of the SAR (W/kg)	0.157	0.159	1.26%
Std of e-field data	3.592	3.652	1.67%
Std of h-field data	0.182	0.176	3.29%
Std of the SAR	0.109	0.112	2.75%

The "e-field" and "h-field" in the table represent the electric field data and the magnetic field data respectively. The "Std" represents Standard deviation of data. Deviation represents $\left| \frac{(co-simulation)-(conventional\ simulation)}{(conventional\ simulation)} \right| \times 100\%$

Figure 3 shows the simulated S-parameter of the RF coil obtained from the conventional and proposed co-simulation methods. It can be seen that the S-parameters agree well for both methods. The maximum deviation of the field distribution data is below 4% and the comparison of two methods are shown in Table II. The EM field and the SAR distribution maps at the same position are shown in Fig. 4.
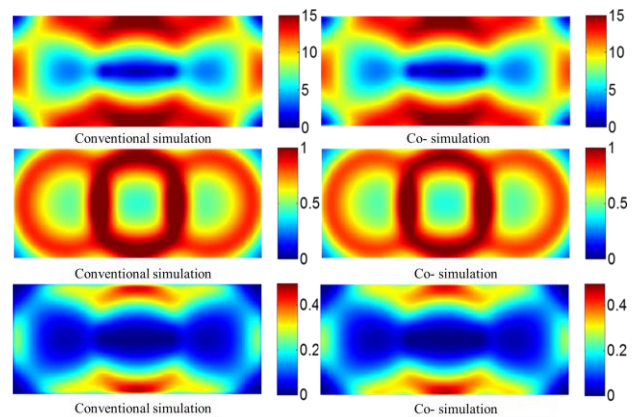

Fig. 4. The electric (top) and magnetic (middle) field distribution and the SAR distribution (bottom) for conventional simulation (left) and co-simulation (right) in water phantom. We use the signal source as the excitation source to calculate the EM field value and SAR data .

V. CONCLUSIONS

Through a 3-channel RF coil simulation, the proposed co-simulation method is much shortened, saving about 79.85% of the time, while the field simulation results deviation between the proposed co-simulation and the conventional method are all less than 4 %. The co-simulation method provide a more efficient simulation choice when calculation speed is critical. The future work will include human tissue and dual-tuned array.

VI. ACKNOWLEDGEMENTS

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