A Distributed Impedance Model for the Shielded 7T Inductive Head Coil

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Introduction

Isolated meshes of the Inductive Resonator (Fig. 1) couple via mutual inductance and develop a "high-pass" mode distribution [1,2]. Transmission line segments placed between neighboring meshes enhance mutual inductance and improve mode separation. Modeling the coil using simple mutual coupling of neighboring meshes, however, does not accurately predict the modes of the shielded 7T head coil. A shield placed close to the coil has the effect of reducing mutual inductance, especially long-range coupling. Here it is shown that the common mode currents of the coil can be identified with transmission lines that use image currents in the shield as return currents. These transmission lines are in turn used to develop a distributed impedance model for the coil that accurately fits the coil modes and predicts the upper frequency limit of the coil.

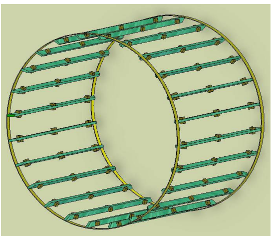

Fig 1. Inductive Coil.

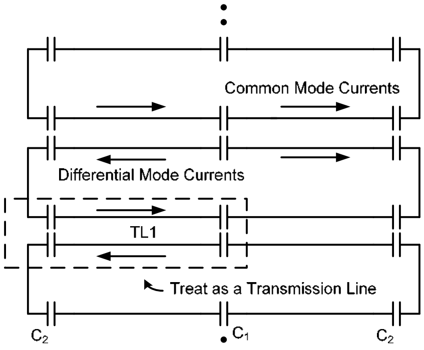

Fig 2a.

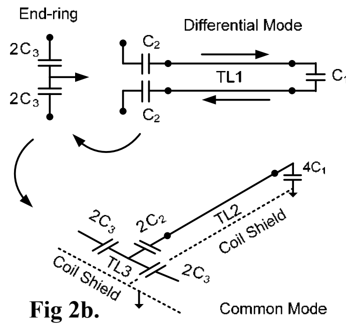

Fig 2b.

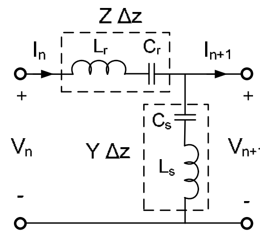

Fig 3. Distributed Impedance Model

Methods

The transmission lines (TL's) for the 24-mesh coil were analyzed as follows: the currents of TL segments forming the legs of the coil can be viewed as a superposition of common- and differential mode currents, as illustrated in Fig. 2a [2]. The differential currents of TL1 create only local flux and are too far away from the shield to be influenced by it. Using the virtual ground at the center of the coil, the differential current mode is shown to contribute to a net capacitance C3 in the end-ring segments, as indicated in Fig. 2b. The common mode currents are the currents of the homogeneous mode, and transmission lines TL2 and TL3 model the currents flowing in the leg segments, in the end-ring segments, and in the shield. Common mode currents flow through capacitors C2 and C1in parallel , so these values are doubled and quadrupled, respectively, for TL2. The capacitors $2C_3$ are each in series with the same capacitance of neighboring legs, so there is a net capacitance of C3 in each end-ring segment of TL3. Natural impedances and velocities of propagation for the TL's were measured using quarter-wave resonators and using segments placed above a copper ground plane. Estimates were also made using common transmission line models [3].

Next, a distributed impedance model was chosen to model the repeating end-ring and leg segments of the coil, as shown in Fig. 3. Two frequencies, $\omega_1^2 = 1/L_rC_r$, and $\omega_2^2 = 1/L_sC_s$ can be identified with the series L and C of each branch. Propagation takes place in the direction of the end-ring, so Δz corresponds to the length of one end-ring segment. The propagation constant for this model is $\beta^2 = -ZY$. But, the Bloch condition requires that $\beta\,\Delta z / 2\pi = k/N$, where k is the mode number. The ω-β relationship for discrete modes can be found by equating these expressions.

Results A 24-mesh, shielded 7T resonator was constructed as described previously [2]. Its 12 modes were measured before coupling circuitry was added to the coil. The ω-β characteristic for the distributed impedance model is shown in Fig. 4 for N=24 and for $\omega_1 > \omega_2$. The modes of Fig. 4 are a manual fit of the ω-β relationship to the twelve mode frequencies measured for the shielded 7T resonator. The fit used $C_r = C_3 = 12.3$ pF, $C_s = 16$ pF, $\omega_1/2\pi = 313$ MHz, and $\omega_2/2\pi = 182$ MHz. A measured value of $L_r = 22.4$ nH for TL3 gives an ω_1 of 303 MHz, which is in good agreement with the fit value. Impedances of TL2 and TL3 were estimated to be 200 Ohms and 152 Ohms, respectively. A Smith Chart analysis of TL2 yields a series resonance of 137 MHz for ω_2, suggesting that a more complex Y impedance may be required to model propagation. The coil frequencies were fit to the high-pass birdcage model using the measured k=1 and k=12 modes and nominal values for C, L, and M [2]. These modes (HP) and those for the transmission line model (TL) are compared in Fig. 5 by subtracting their values from the frequencies measured for the coil. It can be seen that the distributed impedance (TL) model provides a much better fit. A 4-port Tx/Rx 7T head coil has been constructed and used to image a 20 cm Si oil phantom (Fig. 6) and a normal volunteer (Fig. 7). The coil provides good B1 uniformity and coverage over both the phantom and the head.

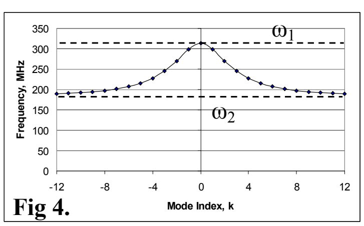

Fig 4.

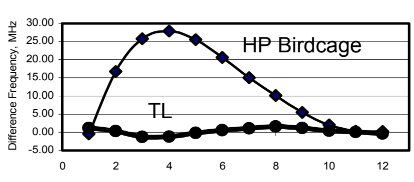

Fig 5.

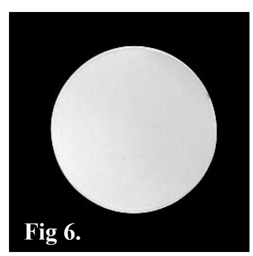

Fig 6.

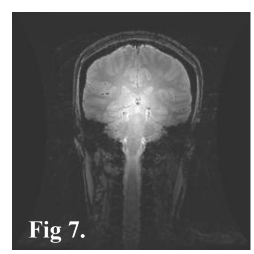

Fig 7.

Conclusions An inductive resonator with a closely spaced shield has been described using a distributed impedance model and three interconnected transmission lines. The transmission lines were used to compute the impedances of the distributed impedance elements. The distributed impedance model identifies the end-ring impedances (ω_1) as critical in determining the upper frequency limit for the coil. Separation of ω_2 from ω_1 is also important for providing good low-order mode separation.

References: 1. H. Wen, AS Chesnick, RS Balaban, US Patent 5,483,163 (Jan 9, 1996). 2. J. Murphy-Boesch, Y-J Yang, Shumin Wang, 14th Annual Meeting ISMRM (2006), p. 215. 3. Fields & Waves in Communications, S.Ramo, J.R. Whinnery, T. van Duzer, John Wiley, N.Y. (1965).