Study of concomitant fields in multipolar PatLoc imaging

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Introduction:

For spatial encoding in magnetic resonance imaging only the $B_z$ component of the magnetic vector is of interest. In conventional imaging $B_z$ is varied linearly along the three directions $x$, $y$ and $z$ to allow for orthogonal and rectangular voxels. One source of voxel distortion or signal dephasing for particular sequences are the concomitant fields $B_x$ and $B_y$ which are unavoidable to fulfill Laplace’s equation. For linear gradients, e.g. for the $x$-gradient, the component $B_z$ along $x$ is transferred into $B_z$ along $z$, Figure 1a/b. With the introduction of non-linear magnetic fields for imaging [1], concomitant fields of higher order harmonics become less trivial. This work studies the concomitant fields of higher order harmonics and of a simplified model of a PatLoc gradient coil [2].

Materials and Methods:

Magnetic fields inside a source-free region can be calculated from Laplace’s equation for the magnetic scalar potential $\nabla^2 \Psi = 0$ [3]. Its solution is given by an infinite series of spherical harmonics [4]

$$\Psi = \sum_{m=0}^{\infty} \sum_{n=-m}^{m} (A_n^m \cos(m\varphi) + B_n^m \sin(m\varphi)) r^n P_n^m(\cos\theta)$$

where $P_n^m$ are the associate Legendre polynomials and $r, \theta, \varphi$ are polar coordinates. From this potential the gradients $B_x$, $B_y$ and $B_z$ of the magnetic field can easily be derived. The maximum of the calculated $B_z$ component inside a unit sphere is used to normalise the magnetic fields to ±1. The total volume in which the magnetic fields are calculated is in arbitrary units of ±2, corresponding to a typical bore diameter to be twice the target spherical region. With the given $B_x$ and $B_y$ components the resulting concomitant field is calculated $B_z = \sqrt{(B_x^2 + B_y^2)}$.

In order to study the impact of the finite coil length, longitudinal and return current paths a step away from harmonic expansions towards wire patterns is required. Second order harmonics are of primary interest here, corresponding to the available PatLoc coil [3]. It is, however, difficult to draw general conclusions from a particular coil implementation. Therefore a vastly simplified model with a low number of parameters has been developed. This model includes a cylindrical magnet bore with a radius 2 with two flat single loop coil elements with a radius 2 placed atop the bore liner separated by a distance of 1/5 to represent one pole of the quadrupolar magnetic field. Total of 4x2 coil elements with alternating current directions are required to mimic a PatLoc gradient coil. $B_x$, $B_y$ and $B_z$ were calculated based on an analytic field formula of a circular current loop. The simulated magnetic field components were scaled to normalize $B_z$ to ±1 inside the unit sphere.

Results & Discussion:

For the linear $x$-gradient (A11) there is no radial component, which corresponds to the common assumption about the concomitant fields of linear gradients [5]. Figure 1a/b shows the scaled $B_z$ component and the corresponding concomitant field $B_x$. Figure 2a/b displays the concomitant field $B_z$ of the second order harmonics A22 (corresponding to the PatLoc encoding field) at $z = 0$ and a 1D representation to visualize the distribution along $y = 0$. Figure 3a/b displays the same plots for the concomitant field $B_z$ of the third order harmonics. The 1D distributions suggest that the radial dependency of the concomitant field $B_z$ is n-1 with the order of the harmonics. Figure 4a displays the encoding component $B_z$ of the model PatLoc coil and Figure 4b the concomitant component $B_x$.

For linear gradients the magnitude of the main and concomitant fields is of the same order. For higher order magnetic fields the concomitant fields have a n-1 distribution with respect to the order of the harmonics. For the calculated harmonics of A22, the maximum $B_z$ inside the sphere at $z=0.5$ is 0.8 (Figure 4a) compared to the calculations from the simplified model with 1. This emphasizes how important a realistic wire path is to estimate the concomitant fields. It is also important to know the concomitant fields to evaluate their effect on imaging and also for prediction of peripheral nerve stimulation which is induced by $B$ and not only by $B_z$.


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