Asymmetric Coils and Travelling Waves

Nicola De Zanche (dezanche@ieee.org), University of Alberta

This lecture covers unconventional methods of volume excitation typically used, respectively, in systems with a noncircular access bore and in those that use ultra-high Larmor frequencies (≥ 300 MHz).

1. Asymmetric Volume Coils

Asymmetric, noncircular volume coils are required in situations where the available access bore is noncircular in cross section, such as for table-top applications [1] or where the gradient bore is noncircular [2]. They consist of ladder network resonators such as the birdcage [3] or TEM [4] coil that have been modified by placing their rungs on a cylindrical surface other than the traditional circular cylinder. Similarly to the traditional designs, the noncircular versions are able to support quadrature operation. The challenge of building asymmetric volume coils is producing homogeneous RF fields.

1.1 *Optimal Current Distributions*

It has been known since the 19th century that a sinusoidal current density on the surface of a cylinder yields a uniform transverse magnetic field in its interior. In the birdcage and TEM coil this surface current density is approximated by discrete currents on uniformly-spaced rungs, and quadrature (circular polarization) is achieved by rotating this sinusoidal current pattern at the Larmor frequency. The n^{th} rung current is written (in phasor notation) as $I_n = I_0 e^{i2\pi n/N} = I_0(\cos 2\pi n/N + i\sin 2\pi n/N)$, where I_0 is the maximum current intensity. To produce uniform transverse magnetic fields within noncircular cylinders, the spacing or current intensities, or both, must be modified. The following are two common approaches.

1.1.1 Conformal Mapping

The conformal mapping method assumes that the currents are distributed according to the above equation, and was first used by Leifer for elliptical coils [5], and subsequently generalized [6]. It begins by identifying a conformal transformation that maps the region *outside* the unit circle to that outside the desired noncircular shape. The transformation is then applied to the uniformly-spaced locations on the unit circle, yielding the new locations of the coil rungs. Tables of conformal maps for common shapes are found in textbooks such as Refs. [7,8], and for other shapes they can be approximated using series expansions [1].

1.1.2 Numerical Optimization

For some shapes it may be necessary or desirable to avoid the conformal mapping method since it can sometimes lead to a nonuniform rung spacing with locally inhomogeneous fields where the spacing is wide. Conformal mapping is also unsuitable for custom rung placement, e.g., to allow access for visual stimulation. In these cases the rung locations can be specified independently and different rung currents from those above must be determined. The numerical optimization begins by generating the field produced by a unit current in each of the rungs. The fields are then linearly combined with coefficients that are chosen to minimize the inhomogeneity within a chosen region of interest. The optimization problem is solved more efficiently if the rung currents, $I_{n,\cos}$ and $I_{n,\sin}$, for the two orthogonal linear modes are optimized separately (Figure 1). Quadrature combination, $I_n = I_{n,\cos} + iI_{n,\sin}$, preserves homogeneity.

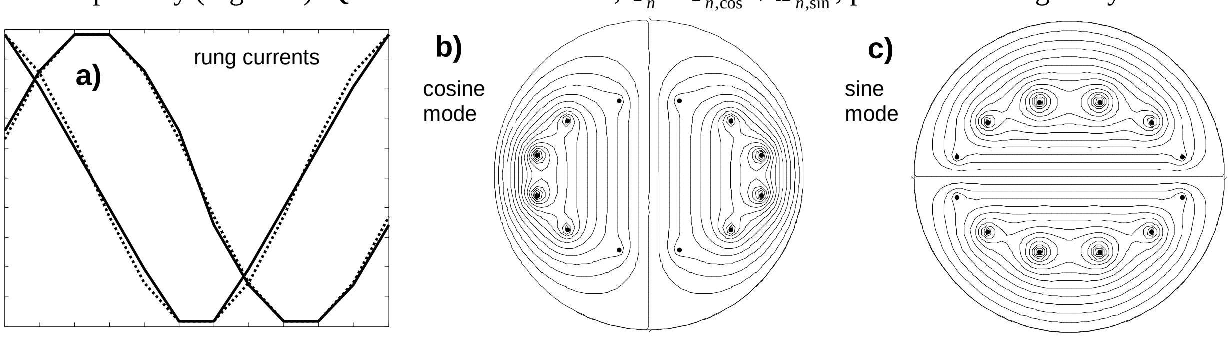

Figure 1: a) currents optimized numerically for an elliptical coil within a circular shield (solid) compared to the unoptimized currents (dashed); b,c) resulting magnetic field lines for cosine and sine modes, respectively.

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1.2 *Ladder Network Capacitances*

The final challenge of designing asymmetric ladder coils is to determine the different capacitances values that tune the coil to produce the desired currents at the appropriate Larmor frequency. Once the geometry of the coil and, if necessary, the optimal rung currents have been determined, the mesh inductance matrix of the ladder network must be obtained, either by measurement or field simulation. The inductance matrix and the desired current patterns are then used to synthesize the capacitance matrix using either numerical optimization or the algebraic method described in [1].

2. Travelling Waves

The excitation and detection of MR signal requires a probe that is capable of producing RF magnetic fields at the Larmor frequency. Traditionally, RF probes or coils were designed to rely only on near-field components because frequencies were too low to observe propagation effects. With advances in superconducting magnet technology the consequently higher frequencies led to significant efforts in MR probe engineering to manage RF inhomogeneity and sensitivity to loading. Travelling-wave MRI [9] addresses these issues by embracing the wave nature of high-frequency RF fields rather than attempting to control it.

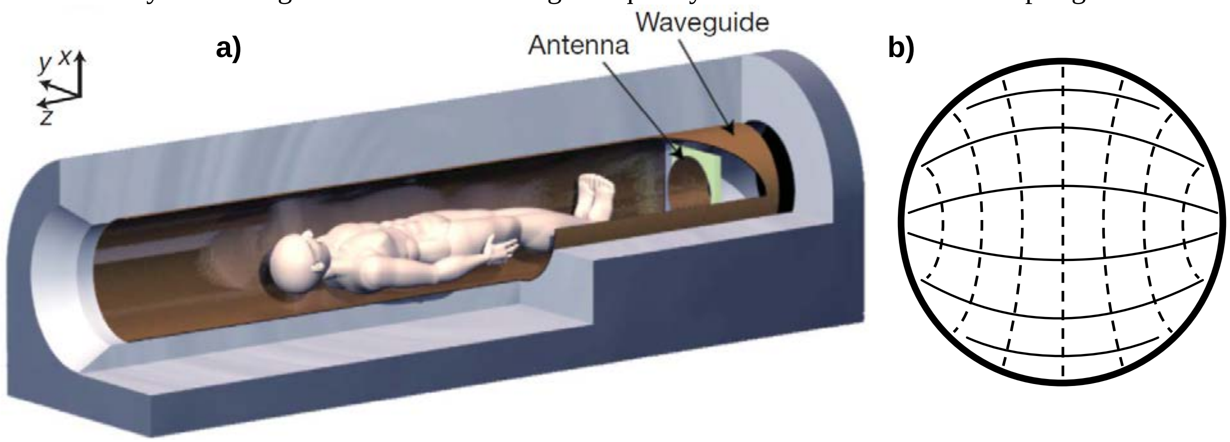

Figure 2: a) travelling-wave MR setup illustrating main components (from [9]); b) magnetic (solid) and electric (dashed) field lines of the TE_{11} mode in the transverse plane of the circular waveguide.

2.1 *Circular Waveguide Theory*

The bore of a cylindrical high-field MR system is typically lined with a thin conductive sheet or mesh which acts as an RF screen against external interference and noise (Figure 2a). It also provides a convenient cylindrical conductive boundary condition that supports guided electromagnetic waves. An empty cylindrical waveguide supports waves with well-known field patterns, or modes [10], each of which has a minimum, or cutoff, frequency below which the waves do not propagate. The presence of this cutoff is the reason why this phenomenon is not observable at standard clinical field strengths. The mode with the lowest cutoff frequency, known as TE_{11}, is shown in Figure 2b.

The cutoff frequency, f_c, of the TE_{11} mode depends on the radius, r, of the cylinder according to $f_c = 0.293c/r$, where c is the speed of light in air. Consequently, the lowest frequency that will propagate within a typical 60-cm MRI bore is 293 MHz, which is conveniently just below the 7 T Larmor frequency. The field homogeneity of this mode appears inferior to that of an unloaded birdcage or TEM coil; however, at these high frequencies RF homogeneity is dominated by the effects of the body's loading, and thus the homogeneities are comparable.

2.2 *Practical implementation*

The lossy dielectric properties of biological tissue create discontinuities within the waveguide which perturb the propagation, leading to reflections and thus axial field inhomogeneities due to standing waves. Dielectric materials can be introduced in the empty portions of the waveguide to reduce these reflections, as well as to lower the cutoff frequency, or to alter the field patterns.

While conventional MR probes require a direct connection, or close inductive coupling, to the sensing coil, travelling-wave MR requires simply a method to launch the waves at one or both of the openings of the bore. The most common approach is to use a patch antenna [10] that is tuned to the Larmor frequency and connected for quadrature excitation similarly to volume coils (Figure 2a). The connection method is the greatest practical difference from that for standard coils which are required to be in close proximity to (i.e., surrounding) the imaging region. The presence of propagating waves allows the fields to extend over the whole length of the bore, rather than being confined only to the region of the birdcage or TEM coil. This remote connection to the imaging volume frees up the space traditionally required for coils, thus improving patient access and comfort.

References

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