The 4-point-drive Litzcage - A Semi-Open MRI RF CP Coil with a Wide Tuning Range

F. David Doty[1], Nathan Laws[1], Laura Holte[1], John P. Staab[1], John Zempel[2], and Joel R. Garbow[2]

1. Doty Scientific, Columbia, SC, USA 2. Washington University, St. Louis, MO, USA

Abstract

We report results from a novel rf coil topology and balancing circuit that demonstrate greatly simplified tuning procedures and improved B_1 homogeneity for circularly polarized (CP) rf MRI volume coils. We denote these coils "**litzcages**", as they embody both paralleled conductor elements with insulated crossovers, similar to that in prior linear "litz coils", and the capacitively segmented phase shifts common to birdcages. Several 4-point-drive balancing circuits were tested that efficiently symmetrize perturbed coils. A combination of these features improves the tuning range by an order of magnitude. The coils and balancing circuits are demonstrated here on rat brain studies in a 38 mm small-animal coil on an open-access platform at 200 MHz.

Introduction

Accommodating wide ranges of loads presents exceptional challenges for small CP coils at high fields. Even with perfect symmetry, at least 12 rungs are generally required for adequate B_1 homogeneity for small-animal MRI birdcages, and such coils typically have a quick tuning range of less than 0.7% with good homogeneity and channel separation. The 8-section birdcage is about twice as tunable and correctable as the 12-section birdcage because it is possible to attach two adjustment variables to nodes at 45^0 with respect to the feed planes, which simplifies the symmetrization problem. A novel 8-section coil has been developed that has B_1 homogeneity comparable to that of the 16-section birdcage but with the tunability of the 8-section birdcage.

An equally important design constraint was to provide maximum accessibility and experimental flexibility in horizontal-bore magnets. For starters, the external rf slotted shield is easily removable. The coilform is not much longer than the rf window, and there are no tuning adjustments (for the user to be concerned with) anywhere near it. If desired, access through the coilform cylindrical surface between the rungs may also be provided. The platform height beyond one end of the coilform is adjustable, and several different size cradles were made. A novel, rat-head holder was developed that proved to be especially advantageous in allowing maximum access for monitoring and surgery, while providing the required rigid positioning to suppress motion artifacts.

Tuning Range Importance

Even though birdcages and related CP coils of many varieties have been in wide usage for eighteen years, most published circuit models leave much to be desired. Part of the problem is that to make the models analytically tractable, it has been customary to either ignore or use highly simplified expressions for most of the couplings (electric and magnetic), circuit losses, and propagation effects.

The standard theoretical model (which ignores all mutual inductances and stray capacitances) gives the following for the modes of the balanced high-pass birdcage:

$$\omega_m = \left[C \left(L_E + 2L_{trl} \sin^2 \frac{\pi m}{N} \right) \right]^{-1/2} \qquad (1)$$

where L_E is the end ring (section) inductance and L_{trl} is the rung inductance.

The next-highest mode, m=1, is the homogeneous (NMR/MRI-useful) mode. The above equation is often off by more than 15% for the homogeneous mode and even more for the other modes. In practice, other modes generally appear that are not predicted by either eq. (1) or the more complex published models, but are generally captured by our circuit models.

For the high-range band-pass birdcage, stray capacitance, propagation effects, and electromagnetic couplings become very significant; and errors in the above equation may be over 20%.

The capacitor accuracy required to place the resonance within the tuning range (the range which keeps the loaded peak-to-peak relative rung current errors below 15%) is extremely tight for two-point quadrature drive. For an 8-rung (balanced) high-pass birdcage, mean-capacitor-value accuracy must be within 1.5%. But a short 18 mm coil of this type (for mouse-brain studies) at 750 MHz, for example, requires tuning capacitors of ~3.9 pF – including stray, which varies from 0.2-0.5 pF, depending on the sample. Hence, the stray variability exceeds the required tolerance by a factor of two, which makes this coil and tuning method (2-point-drive) impractical. Moreover, even if ideally tuned, the 8-rung birdcage has inadequate B1 homogeneity for most purposes, and the tolerance requirements on the 16-rung birdcage are nearly twice as stringent.

Methods

Each rung in the 8-section birdcage has been replaced by two parallel rungs, as partially shown in **Figure 1** for the high-pass (HP) case, with an insulated crossover at the center; so it has 16 rungs, but only 8 rf sections. From the axial symmetry, each of the two parallel (identical) rungs per section must carry equal current, irrespective of the section's relative phase. From an rf circuit perspective, the homogeneous mode is similar to that of Crozier's parallel-rung 8-section birdcage, which is nearly identical to the conventional birdcage from an rf perspective. The reduction in stray capacitance and self-inductance in the litzcage compared to the 8-rung birdcage allows it to tune ~20% higher (to *fd*=50 MHz-m). We optimize the conductor widths such that the product of the magnetic filling factor and loaded Q, $h_F Q_L$ (hence, S/N), is maximized and B_1 inhomogeneity is minimized.

A low-pass (LP) litzcage of 3.8 cm diameter and 3 cm FOV length was constructed for use inside a slotted-shield tube of 10 cm diameter. The coil is mounted on a platform that permits convenient, open, adjustable access for rat-brain studies. The 4-point-drive circuit, half of which is shown in **Figure 2**, was found to reduce worst-case rung-current errors by a factor of four and improve channel isolation by at least 5 dB compared to 2-point drive circuits. Half-lambda coax lines between nodes 180^0 apart maintain precise symmetry. The combination of three novel features: 1) 4-point balanced drive with orthogonal symmetrization, 2) the 8-section litzcage, and 3) tuned variable capacitors – increases the tuning range of homogeneous CP MRI coils by an order of magnitude compared to standard CP methods.

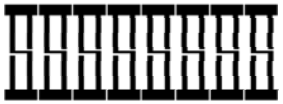


Figure 1. The first-surface of the litzcage pattern is shown. (The other surface on the laminate completes the central crossovers.) The pattern wraps around a cylinder aligned with B_0 (vertical in this view) and generates a transverse CP B_1.

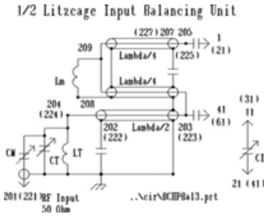


Figure 2. One channel of a 4-point-drive balancing network.

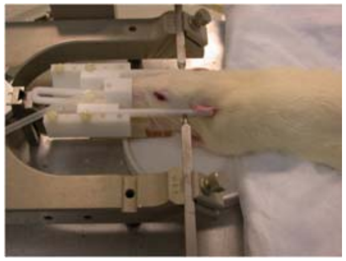
Tuning Range Advantages

Our experience agrees with published discussions that the maximum useful (quick) tuning range for a low-field 8-section BHP birdcage with 2-point-drive is 1.3%. The sample-induced tuning shift for a high-field small-animal coil can exceed 8% – up to 12 times the quick tuning range of a 12-rung hybrid birdcage with 2-point-drive.

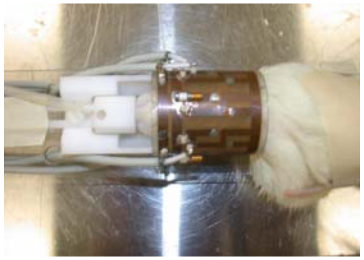
We have developed several highly effective 4-point-drive tune/balance/match circuits which provide an order of-magnitude increase in tuning range for birdcages without spoiling B1 homogeneity or isolation. When combined with our 8-section litzcage, one then has B1 homogeneity comparable to that of an *ideal* 16-rung birdcage (i.e., perfect precision and no variability in strays) with well over an order of magnitude greater tuning range, as needed for practical small-animal applications. One-channel of our currently preferred quad-balance network is shown in **Figure 2**. The two series quarter-lambda's force the needed symmetry; the unlabeled capacitors are simply eddy-current-blocking capacitors (rf shorts); LM is used to move the common mode well away from the differential mode; and LT tunes out half of the sum of the tuning variable CT and the mean match variable CM, thereby doubling the useful tuning range. The half-lambda feed line allows convenient placement of the variable capacitors well away from the coil. With low-loss coax lines (e.g., Belden type 1855A, which is only 4 mm in diameter), the total signal loss added by the balancing network is under 5% for typical small-animal coils.

Results

The calculations predicted a 90^0 pulse length of 21 μs for a square 100 W pulse on a rat head, though measured efficiency was somewhat lower. S/N was comparable to what had previously been achieved with optimized 3 cm birdcages. The coil easily tuned and matched to the full range of sample sizes and consistently obtained better B_1 homogeneity than that of other birdcages.

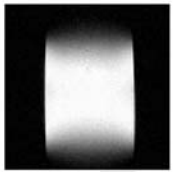


From animal surgery…

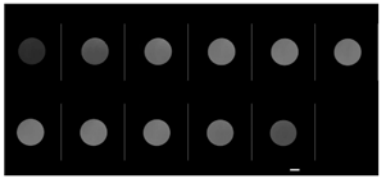


Into the coil… easily
- Space to adjust
- Space to run monitoring devices

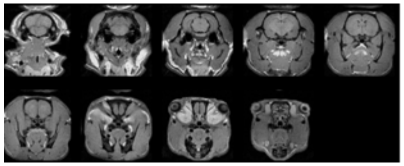
MR Images



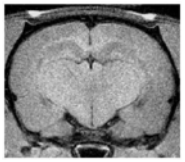
SEMS trans, water tube
3.8 cm coil
TR=1 sec, TE=20 msec 128x128 5 cm FOV, nt=2



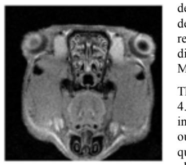
SEMS trans, smaller water tube
3.8 cm coil
1 mm slices every 3 mm
TR=4 sec, TE=20 msec 128x128 3 cm FOV, nt=4



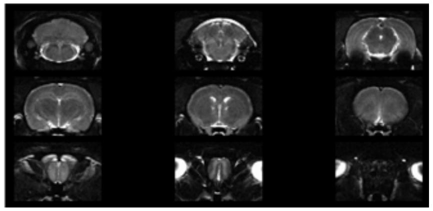
MDEFT trans, rat brain T1
3.8 cm coil
1 mm slices every 3 mm,
Tr 1.5 sec/T_{MD}=0.75 sec, te 14 msec 256x256, 3 cm FOV, nt=4



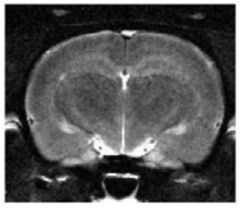
T1 weighted image



T1 weighted image



SEMS trans, rat brain T2
3.8 cm coil
1 mm slices every 3 mm,
Tr 2 sec, Te 120 msec 256x256, 3 cm FOV, nt=4



T2 weighted image

Conclusions

It seems the absence of any one of the three tuning-range-enhancing features produces a less-functional, less user-friendly coil. Also, the authors found a tremendous benefit in the open coil mounting and platform design because of the ease with which a complicated physiologically monitored rat could be mounted, accommodated, and removed.

Other Applications, to 750 MHz

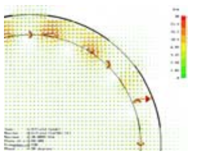
While the focus of the study presented here was rat models at 200 MHz, we note that we have also seen strong advantages in the Circular Polarization 4-point-drive Doty Litzcage for MRI in a 20 cm x 27 cm 200 MHz coil for studies of larger animals and in an 18 mm sample at 750 MHz. To our knowledge, prior CP coils have not been successful above 600 MHz with sample sizes larger than 5 mm. (This tends to support our analysis, which suggests practical difficulties in CP coils increase quadratically with frequency.) The circuit simulations indicate overall rf efficiency exceeded 85%, which is roughly consistent with obtaining a 22 μs π/2 with under 50 W for a pure water sample (lightly loaded coil). Both B_1 and B_0 homogeneity appeared excellent. It appears quite feasible to extend this coil design to easily accommodate the adult mouse or small rat at 800 MHz. More information on these and many other applications, including human head at 3 T, are available upon request.

Full-wave Simulations of Complete MRI RF Coils

We, very recently, performed rather extensive evaluations of three of the most advanced commercial codes. We found REMCOM's XFDTD to be useless for evaluating Q_L and η_F or $B_1/P_i^{1/2}$ in complete, small-animal, coil systems. Ansoft's HFSS 8.5 is of some utility for these problems and perhaps version 9.0 (coming in a few months) will be quite useful. We have come to the conclusion that of those we evaluated, CST MWS 4.2 really stands out in front, especially for cases where a very high aspect ratio (ratio of largest to smallest cell-size) will be required and in situations where it is important to include the effects of tuning and matching circuits, coil losses, slotted HF shields, radiation, real samples, and coil asymmetries. All of these effects are often quite important, especially in high-field coils for small-animal research.

We are still in the very early stages of applying the powerful simulation and optimization capabilities of CST MWS 4.2 to our CP litzcages and linear litz coils. One early conclusion is that the (proprietary) rf-augmented Biot-Savart software *COILS,* which we developed in-house (mostly, six years ago, that allowed us to develop our novel linear litz coils and crescent gradient coils) is remarkably accurate and powerful for complex coils with frequency-diameter products (*fd*) up to ~15 MHz-m (e.g., a 50 mm coil at 300 MHz) with saline phantoms.

The Figures below compare some field calculations from CST MWS 4.2 and *COILS* 6.1 for a litzcage where *fd* =24 MHz-m. The arrows in the CST output (left) and the directed line segments in the *COILS* output (right) show the expected H field for the m=1 mode for one quadrant of the transverse (x-y) plane about 2 cm above center. (The phases here differed by 90°). The small circles in the *COILS* output are approximate locations of the current elements, on the surfaces of the litzcage rungs and external shield. (In the COILS case, the external cylindrical shield was solid.) Although not evident here, the CST simulations include all details in the matching network, slotted shield, insulated crossovers, tuning capacitors, etc. The primary modes (m_0, m_1, m_2, and any parasitics between m_0 and m_2) are normally predicted within ~1%, Q_L is generally correct within ~20% (which is comparable to experimental accuracy), and B_1 is usually accurate within 10%.



H-Field calculations from CST MWS 4.2 for a litzcage (*fd* =24 MHz-m)

H-Field calculations from *COILS* 6.1 for a litzcage (*fd* =24 MHz-m)