FEM Based Design and Simulation Tool for MRI Birdcage Coils Including Eigenfrequency Analysis

Necip Gurler and Yusuf Ziya Ider

Electrical and Electronics Engineering Department
Bilkent University, Ankara, TURKEY

COMSOL CONFERENCE EUROPE 2012

11.10.2012
Milan, Italy

COMSOL CONFERENCE EUROPE 2012

Outline

Outline

1. Introduction
   - RF coils in MRI
   - RF birdcage coils
   - Design and simulation of RF birdcage coils
2. Motivation
   - Review of previous studies
   - Problem definition
   - Our work
3. Methods
   - FEM Models of Birdcage Coils
   - Frequency Domain Analysis
   - Eigenfrequency Analysis
   - Software Tool
4. Experimental Results
5. Conclusion

Outline

What Do the RF Coils Serve in MRI?

- generate RF magnetic field (B_1 field) at the Larmor frequency
- receive RF signals at the same frequency

Source of figures: http://www.cis.rit.edu/htbooks/mri/chap-9/chap-9.htm

RF Birdcage Head Coil Example

Source of figure: http://www.healthcare.philips.com

Outline

RF Birdcage Coils

RF Birdcage Coils

based on the lumped element delay line (Hayes et al., 1985)

RF Birdcage Coils

based on the lumped element delay line (Hayes et al., 1985)

widely used in MRI

RF Birdcage Coils

based on the lumped element delay line (Hayes et al., 1985)

widely used in MRI

Advantages

RF Birdcage Coils

based on the lumped element delay line (Hayes et al., 1985)

widely used in MRI

Advantages

- very homogeneous RF magnetic field

RF Birdcage Coils

based on the lumped element delay line (Hayes et al., 1985)

widely used in MRI

Advantages

- very homogeneous RF magnetic field
- high signal-to-noise ratio (SNR)

RF Birdcage Coils

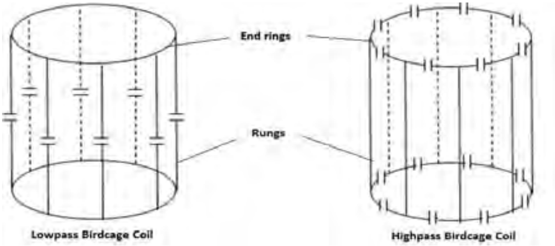
based on the lumped element delay line (Hayes et al., 1985)

widely used in MRI

Advantages

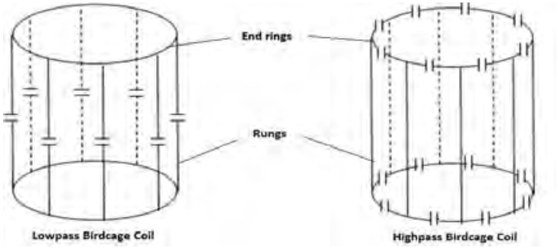
- very homogeneous RF magnetic field
- high signal-to-noise ratio (SNR)
- quadrature excitation and reception capability

Birdcage Coils Consist of...



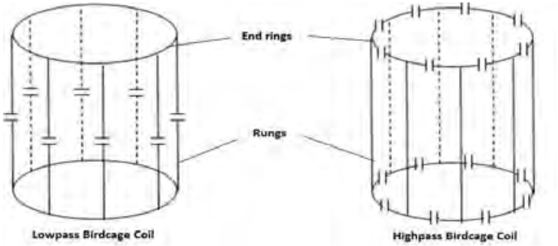
Birdcage Coils Consist of...

- two circular end rings connected by N equally spaced rungs (or legs)



Birdcage Coils Consist of...

- two circular end rings connected by N equally spaced rungs (or legs)
- capacitors on the rungs or end rings or both



Resonance Behavior of Birdcage Coils

A birdcage coil with N number of rungs and equal valued capacitors has

Resonance Behavior of Birdcage Coils

A birdcage coil with N number of rungs and equal valued capacitors has

- N/2 resonant modes (m=1,2... N/2)

Resonance Behavior of Birdcage Coils

A birdcage coil with N number of rungs and equal valued capacitors has

- N/2 resonant modes (m=1,2... N/2)
  - degenerate mode pairs - two modes with the same frequency

Resonance Behavior of Birdcage Coils

A birdcage coil with N number of rungs and equal valued capacitors has

- N/2 resonant modes (m=1,2... N/2)
  - degenerate mode pairs - two modes with the same frequency
- end ring resonant mode (m=0)

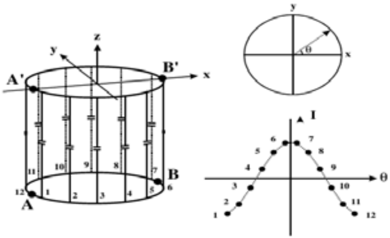
Resonance Behavior of Birdcage Coils

A birdcage coil with N number of rungs and equal valued capacitors has

- N/2 resonant modes (m=1,2... N/2)
  - degenerate mode pairs - two modes with the same frequency
- end ring resonant mode (m=0)
  - currents only flow in the end rings - Helmholtz pair

Which Resonant Mode is used in MRI?

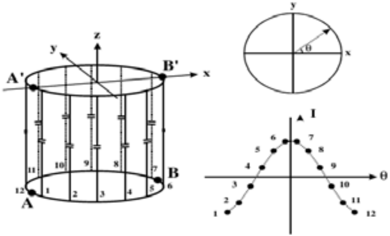
- most homogeneous B_1 field
- sinusoidal current distribution in the rungs for $m = 1$ mode



Source of figure: M. Lupu, MAGMA, 2004, 17, 363-371

Which Resonant Mode is used in MRI?

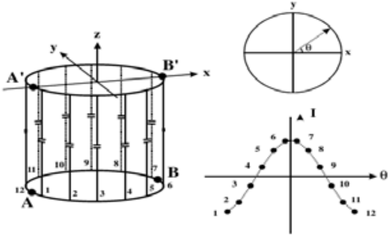
- most homogeneous B_1 field
- sinusoidal current distribution in the rungs for $m = 1$ mode



Source of figure: M. Lupu, MAGMA, 2004, 17, 363-371

Which Resonant Mode is used in MRI?

- most homogeneous B_1 field
- sinusoidal current distribution in the rungs for $m = 1$ mode



Source of figure: M. Lupu, MAGMA, 2004, 17, 363-371

Outline

1. Introduction
   - RF coils in MRI
   - RF birdcage coils
   - Design and simulation of RF birdcage coils
2. Motivation
   - Review of previous studies
   - Problem definition
   - Our work
3. Methods
   - FEM Models of Birdcage Coils
   - Frequency Domain Analysis
   - Eigenfrequency Analysis
   - Software Tool
4. Experimental Results
5. Conclusion

Designing a RF Birdcage Coil

In order to generate a homogeneous B_1 field at the desired frequency;

- use the correct capacitance value
  - calculate an initial capacitance value
  - tuning and matching procedures
- knowing resonant modes of the birdcage coil
  - tuning and matching procedures can be done without interfering with the other modes
  - m=0 mode is used in open MRI systems

Designing a RF Birdcage Coil

In order to generate a homogeneous B_1 field at the desired frequency;

- use the correct capacitance value
  - calculate an initial capacitance value
  - tuning and matching procedures
- knowing resonant modes of the birdcage coil
  - tuning and matching procedures can be done without interfering with the other modes
  - m=0 mode is used in open MRI systems

Designing a RF Birdcage Coil

In order to generate a homogeneous B_1 field at the desired frequency;

- use the correct capacitance value
  - calculate an initial capacitance value
  - tuning and matching procedures
- knowing resonant modes of the birdcage coil
  - tuning and matching procedures can be done without interfering with the other modes
  - m=0 mode is used in open MRI systems

Designing a RF Birdcage Coil

In order to generate a homogeneous B_1 field at the desired frequency;

- use the correct capacitance value
  - calculate an initial capacitance value
  - tuning and matching procedures
- knowing resonant modes of the birdcage coil
  - tuning and matching procedures can be done without interfering with the other modes
  - m=0 mode is used in open MRI systems

Designing a RF Birdcage Coil

In order to generate a homogeneous B_1 field at the desired frequency;

- use the correct capacitance value
  - calculate an initial capacitance value
  - tuning and matching procedures

- knowing resonant modes of the birdcage coil
  - tuning and matching procedures can be done without interfering with the other modes
  - m=0 mode is used in open MRI systems

Designing a RF Birdcage Coil

In order to generate a homogeneous B_1 field at the desired frequency;

- use the correct capacitance value
  - calculate an initial capacitance value
  - tuning and matching procedures

- knowing resonant modes of the birdcage coil
  - tuning and matching procedures can be done without interfering with the other modes
  - m=0 mode is used in open MRI systems

Designing a RF Birdcage Coil

In order to generate a homogeneous B_1 field at the desired frequency;

- use the correct capacitance value
  - calculate an initial capacitance value
  - tuning and matching procedures
- knowing resonant modes of the birdcage coil
  - tuning and matching procedures can be done without interfering with the other modes
  - m=0 mode is used in open MRI systems

Designing a RF Birdcage Coil

In order to generate a homogeneous B_1 field at the desired frequency;

- use the correct capacitance value
  - calculate an initial capacitance value
  - tuning and matching procedures
- knowing resonant modes of the birdcage coil
  - tuning and matching procedures can be done without interfering with the other modes
  - m=0 mode is used in open MRI systems

Designing a RF Birdcage Coil

In order to generate a homogeneous B_1 field at the desired frequency;

- use the correct capacitance value
  - calculate an initial capacitance value
  - tuning and matching procedures
- knowing resonant modes of the birdcage coil
  - tuning and matching procedures can be done without interfering with the other modes
  - m=0 mode is used in open MRI systems

Simulating a RF Birdcage Coil

Solving for the electromagnetic fields of a birdcage coil at the specified frequency.

- B_1 field distribution inside the coil
- specific absorption rate (SAR) at any object
- variation of any electromagnetic field variables with respect to frequency

Simulating a RF Birdcage Coil

Solving for the electromagnetic fields of a birdcage coil at the specified frequency.

- B_1 field distribution inside the coil
- specific absorption rate (SAR) at any object
- variation of any electromagnetic field variables with respect to frequency

Simulating a RF Birdcage Coil

Solving for the electromagnetic fields of a birdcage coil at the specified frequency.

- B_1 field distribution inside the coil
- specific absorption rate (SAR) at any object
- variation of any electromagnetic field variables with respect to frequency

Simulating a RF Birdcage Coil

Solving for the electromagnetic fields of a birdcage coil at the specified frequency.

- B_1 field distribution inside the coil
- specific absorption rate (SAR) at any object
- variation of any electromagnetic field variables with respect to frequency

Outline

Outline

Studies on Designing a Birdcage Coil

Tropp, 1989
analyzing low-pass birdcage resonator - using lumped circuit element model and perturbation theory

Jin, 1989
resonant modes calculation - lumped circuit element model

Pascone et al., 1991
analyzing both low-pass and high-pass birdcage coil - using transmission line theory

Leifer, 1997
resonant modes calculation - using discrete Fourier transform

Chin et al., 2002
capacitance calculation - lumped circuit element model

Studies on Designing a Birdcage Coil

Tropp, 1989
analyzing low-pass birdcage resonator - using lumped circuit element model and perturbation theory

Jin, 1989
resonant modes calculation - lumped circuit element model

Pascone et al., 1991
analyzing both low-pass and high-pass birdcage coil - using transmission line theory

Leifer, 1997
resonant modes calculation - using discrete Fourier transform

Chin et al., 2002
capacitance calculation - lumped circuit element model

Studies on Designing a Birdcage Coil

Tropp, 1989
analyzing low-pass birdcage resonator - using lumped circuit element model and perturbation theory

Jin, 1989 - `MRIEM Software Tool`
resonant modes calculation - lumped circuit element model

Pascone et al., 1991
analyzing both low-pass and high-pass birdcage coil - using transmission line theory

Leifer, 1997
resonant modes calculation - using discrete Fourier transform

Chin et al., 2002
capacitance calculation - lumped circuit element model

Lumped Circuit Element Model

- end rings and rungs are modeled as inductors
- self and mutual inductances are calculated using handbook formulas
- equivalent circuit model (LC network) is solved using Kirchoff's voltage and current laws

Lumped Circuit Element Model

- end rings and rungs are modeled as inductors
- self and mutual inductances are calculated using handbook formulas
- equivalent circuit model (LC network) is solved using Kirchoff's voltage and current laws

Lumped Circuit Element Model

- end rings and rungs are modeled as inductors
- self and mutual inductances are calculated using handbook formulas
- equivalent circuit model (LC network) is solved using Kirchoff's voltage and current laws

Lumped Circuit Element Model

- end rings and rungs are modeled as inductors
- self and mutual inductances are calculated using handbook formulas
- equivalent circuit model (LC network) is solved using Kirchoff's voltage and current laws

Lumped Circuit Element Model

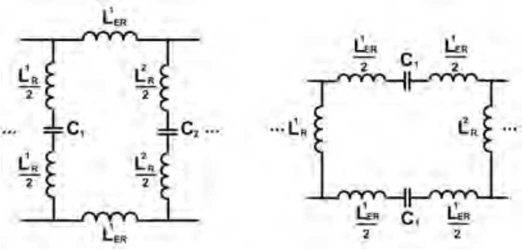


Figure: Equivalent lumped circuit element models for low-pass and high-pass birdcage coils

Outline

Limitation of Lumped Circuit Element Model

There are some limitations of using lumped circuit element model

- heavily depends on the inductance calculations

Limitation of Lumped Circuit Element Model

There are some limitations of using lumped circuit element model in the capacitance and resonant modes calculations:

- heavily depends on the inductance calculations

Limitation of Lumped Circuit Element Model

There are some limitations of using lumped circuit element model in the capacitance and resonant modes calculations:

- heavily depends on the inductance calculations

Limitation of Lumped Circuit Element Model

There are some limitations of using lumped circuit element model in the capacitance and resonant modes calculations:

- heavily depends on the inductance calculations which are made under the quasi-static assumption

Limitation of Lumped Circuit Element Model

There are some limitations of using lumped circuit element model in the capacitance and resonant modes calculations:

- heavily depends on the inductance calculations which are made under the quasi-static assumption

Example: $$L = 0.002l \left[\ln\left(\frac{2l}{B}\right) + 0.5 \right]$$

Limitation of Lumped Circuit Element Model

There are some limitations of using lumped circuit element model in the capacitance and resonant modes calculations:

- heavily depends on the inductance calculations which are made under the quasi-static assumption

Example: $$L = 0.002l \left[\ln\left(\frac{2l}{B}\right) + 0.5 \right]$$

$$\textit{frequency} \uparrow$$

Limitation of Lumped Circuit Element Model

There are some limitations of using lumped circuit element model in the capacitance and resonant modes calculations:

- heavily depends on the inductance calculations which are made under the quasi-static assumption

Example:

$$L = 0.002l\left[\ln\left(\frac{2l}{B}\right) + 0.5\right]$$

$$\textit{frequency} \uparrow \textit{error} \uparrow$$

Modelling a Transmission Line as a Lumped Circuit Element

Deutsch et al., 1997

There is an important criterion

Modelling a Transmission Line as a Lumped Circuit Element

Deutsch et al., 1997

There is an important criterion - used for determining whether a wire can be modeled as lumped circuit element or not -

Modelling a Transmission Line as a Lumped Circuit Element

Deutsch et al., 1997

There is an important criterion - used for determining whether a wire can be modeled as lumped circuit element or not - which is given as

Modelling a Transmission Line as a Lumped Circuit Element

Deutsch et al., 1997

There is an important criterion - used for determining whether a wire can be modeled as lumped circuit element or not - which is given as

$$\textit{length of wire} \leq \frac{\lambda}{20}$$

where λ is the wavelength.

Outline

What Have We Done in this Study?

What Have We Done in this Study?

We have first developed **FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics.

What Have We Done in this Study?

We have first developed **FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics.

Using these models;

What Have We Done in this Study?

We have first developed **FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics.

Using these models;

- Two FEM based simulation methods

What Have We Done in this Study?

We have first developed **FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics.

Using these models;

- Two FEM based simulation methods
  - Frequency Domain Analysis

What Have We Done in this Study?

We have first developed **FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics.

Using these models;

- Two FEM based simulation methods
  - Frequency Domain Analysis
  - Eigenfrequency Analysis

What Have We Done in this Study?

We have first developed **FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics.

Using these models;

- Two FEM based simulation methods
  - Frequency Domain Analysis
  - Eigenfrequency Analysis
- Software Tool

What Have We Done in this Study?

We have first developed **FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics.

Using these models;

- Two FEM based simulation methods
  - Frequency Domain Analysis
  - Eigenfrequency Analysis
- Software Tool
  - FEM-FDA-EFAT

What Have We Done in this Study?

We have first developed **FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics.

Using these models;

- Two FEM based simulation methods
  - Frequency Domain Analysis
  - Eigenfrequency Analysis
- Software Tool
  - FEM-FDA-EFAT

A handmade low-pass birdcage coil is constructed.

Outline

Outline

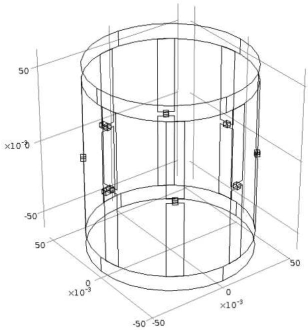
Geometry

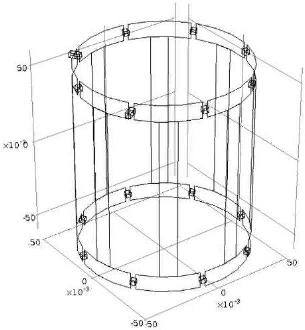
Geometry

- low-pass and high-pass birdcage coils are geometrically modeled in the simulation environment

Geometry

- low-pass and high-pass birdcage coils are geometrically modeled in the simulation environment





Adding Physics

Adding Physics

- Radio Frequency Branch $\rightarrow$ Electromagnetic Waves Interface

Adding Physics

- Radio Frequency Branch $\rightarrow$ Electromagnetic Waves Interface
- solves the electromagnetic wave equation for the time harmonic and eigenfrequency problem

Adding Physics

- Radio Frequency Branch $\rightarrow$ Electromagnetic Waves Interface
- solves the electromagnetic wave equation for the time harmonic and eigenfrequency problem

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2 \left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0} \right) \mathbf{E} = 0$$

Boundary Conditions

Boundary Conditions

- boundaries of rungs, end rings, capacitor plates and RF shield are assigned to Perfect Electric Conductor (PEC)

Boundary Conditions

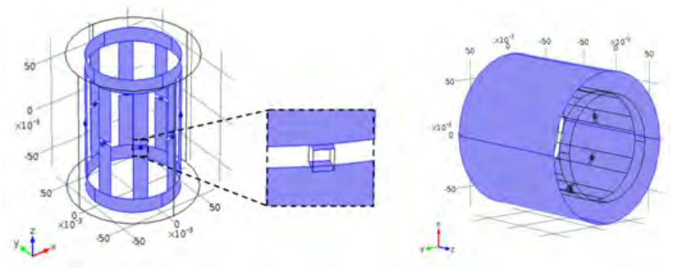
- boundaries of rungs, end rings, capacitor plates and RF shield are assigned to Perfect Electric Conductor (PEC)

$$\mathbf{n} \times \mathbf{E} = 0$$

Boundary Conditions

- boundaries of rungs, end rings, capacitor plates and RF shield are assigned to Perfect Electric Conductor (PEC)

$$\mathbf{n} \times \mathbf{E} = 0$$



Boundary Conditions

Boundary Conditions

- we need to prevent reflections from the outer boundary of the solution domain

Boundary Conditions

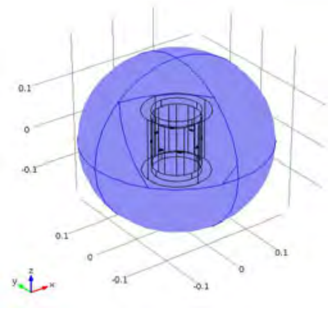
- we need to prevent reflections from the outer boundary of the solution domain
- scattering boundary condition $\rightarrow$ for boundaries

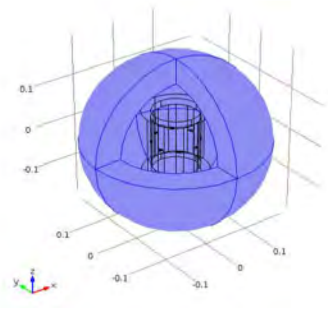
Boundary Conditions

- we need to prevent reflections from the outer boundary of the solution domain
- scattering boundary condition $\rightarrow$ for boundaries
- perfectly matched layer $\rightarrow$ for domain

Boundary Conditions

- we need to prevent reflections from the outer boundary of the solution domain
- scattering boundary condition → for boundaries
- perfectly matched layer → for domain





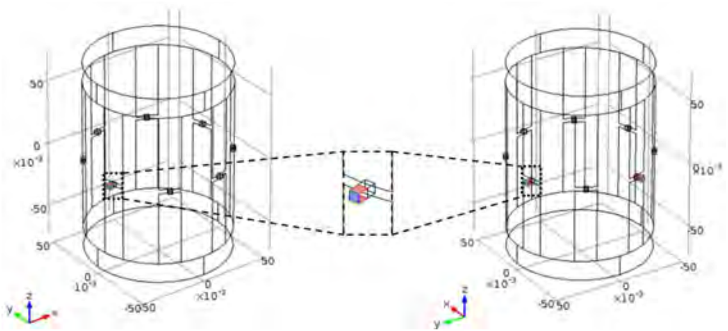
Boundary Conditions

Boundary Conditions

- In frequency domain analysis, lumped port boundary condition is used for voltage excitation ($Z_{port} = \frac{V_{port}}{I_{port}}$)

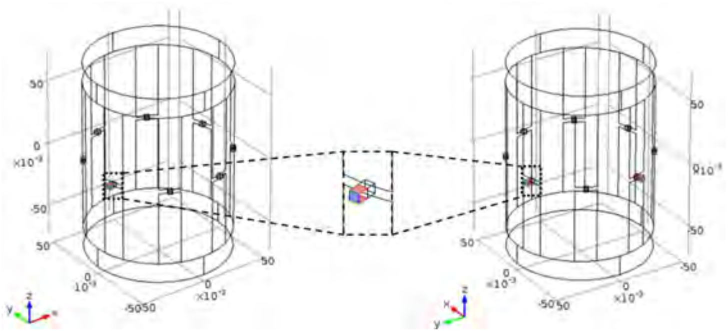
Boundary Conditions

- In frequency domain analysis, lumped port boundary condition is used for voltage excitation ($Z_{port} = \frac{V_{port}}{I_{port}}$)



Boundary Conditions

- In frequency domain analysis, lumped port boundary condition is used for voltage excitation ($Z_{port} = \frac{V_{port}}{I_{port}}$)



- In eigenfrequency analysis, no source is applied

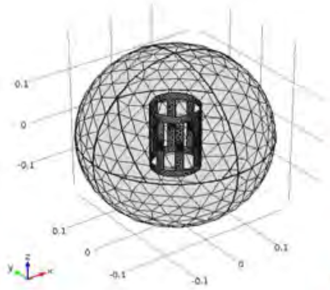
Mesh

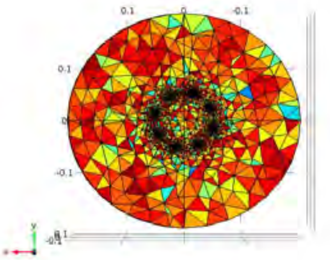
Mesh

- $(\textit{Element Size}) << \frac{\lambda}{5}$

Mesh

- $(\textit{Element Size}) << \frac{\lambda}{5}$





Outline

Simulation of a Birdcage Coil

Simulation of a Birdcage Coil

solves for the electromagnetic fields in the solution domain

Simulation of a Birdcage Coil

solves for the electromagnetic fields in the solution domain

- at the desired frequency (or frequencies)

Simulation of a Birdcage Coil

solves for the electromagnetic fields in the solution domain

- at the desired frequency (or frequencies)
- for the specified capacitance value

Simulation of a Birdcage Coil

solves for the electromagnetic fields in the solution domain

- at the desired frequency (or frequencies)
- for the specified capacitance value

In Frequency Domain Analysis;

Simulation of a Birdcage Coil

solves for the electromagnetic fields in the solution domain

- at the desired frequency (or frequencies)
- for the specified capacitance value

In Frequency Domain Analysis;

- loaded (or unloaded) birdcage coils

Simulation of a Birdcage Coil

solves for the electromagnetic fields in the solution domain

- at the desired frequency (or frequencies)
- for the specified capacitance value

In Frequency Domain Analysis;

- loaded (or unloaded) birdcage coils
- shielded (or unshielded) birdcage coils

Simulation of a Birdcage Coil

solves for the electromagnetic fields in the solution domain

- at the desired frequency (or frequencies)
- for the specified capacitance value

In Frequency Domain Analysis;

- loaded (or unloaded) birdcage coils
- shielded (or unshielded) birdcage coils
- linear or quadrature excitation

Simulation Results

Simulation Results

three different scenarios;

Simulation Results

three different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil

Simulation Results

three different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 8-leg low-pass birdcage coil

Simulation Results

three different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 8-leg low-pass birdcage coil
- loaded and shielded 16-leg high-pass birdcage coil

Simulation Results

three different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 8-leg low-pass birdcage coil
- loaded and shielded 16-leg high-pass birdcage coil

electromagnetic field distributions

Simulation Results

three different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 8-leg low-pass birdcage coil
- loaded and shielded 16-leg high-pass birdcage coil

electromagnetic field distributions

- H^{+} and H^{-}

Simulation Results

three different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 8-leg low-pass birdcage coil
- loaded and shielded 16-leg high-pass birdcage coil

electromagnetic field distributions

- H^+ and H^-

$$H^+ = \frac{H_x + iH_y}{2} \qquad H^- = \frac{(H_x - iH_y)^*}{2}$$

Simulation Results

three different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 8-leg low-pass birdcage coil
- loaded and shielded 16-leg high-pass birdcage coil

electromagnetic field distributions

- H^+ and H^-

$$H^+ = \frac{H_x + iH_y}{2} \qquad H^- = \frac{(H_x - iH_y)^*}{2}$$

- E-field

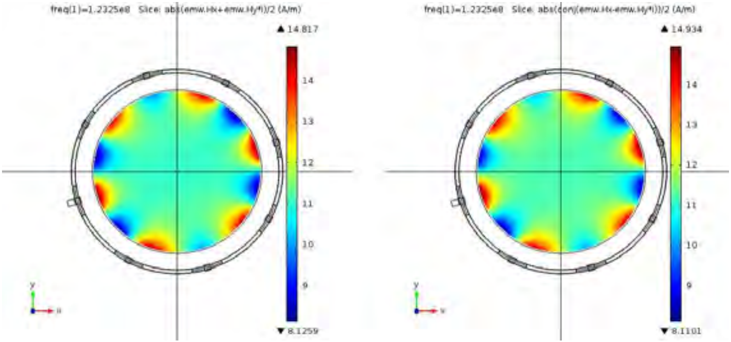
Simulation Results - 1^{st} Scenario Unloaded and Unshielded 8-leg Low-pass BC

Simulation Results - 1^{st} Scenario Unloaded and Unshielded 8-leg Low-pass BC

$\mathbf{H}^{+}$ and $\mathbf{H}^{-}$ $\rightarrow$ for linear excitation

Simulation Results - 1^{st} Scenario
Unloaded and Unshielded 8-leg Low-pass BC

$\mathbf{H}^{+}$ and $\mathbf{H}^{-}$ $\rightarrow$ for linear excitation

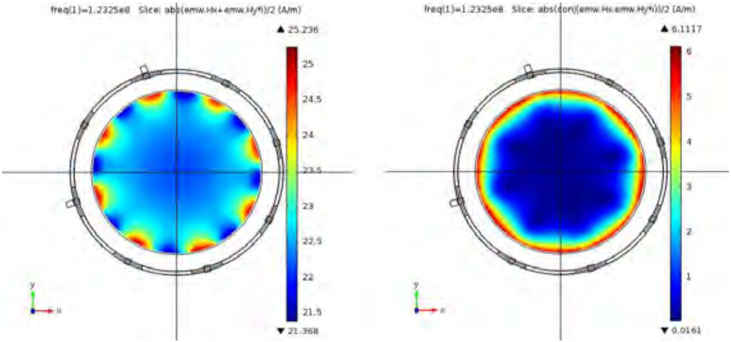


Simulation Results - 1^{st} Scenario
Unloaded and Unshielded 8-leg Low-pass BC

$\mathbf{H}^{+}$ and $\mathbf{H}^{-}$ $\rightarrow$ for quadrature excitation

Simulation Results - 1^{st} Scenario
Unloaded and Unshielded 8-leg Low-pass BC

$\mathbf{H}^{+}$ and $\mathbf{H}^{-}$ $\rightarrow$ for quadrature excitation

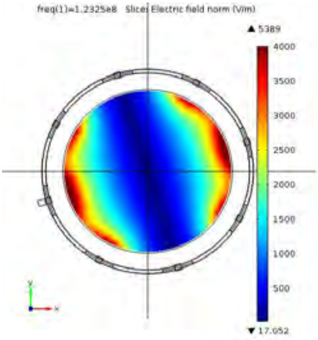


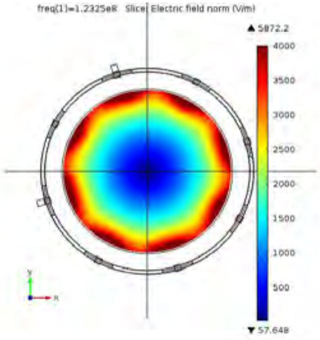
Simulation Results - 1^{st} Scenario Unloaded and Unshielded 8-leg Low-pass BC

Electric field $\rightarrow$ for linear and quadrature excitation

Simulation Results - 1^{st} Scenario Unloaded and Unshielded 8-leg Low-pass BC

Electric field $\rightarrow$ for linear and quadrature excitation



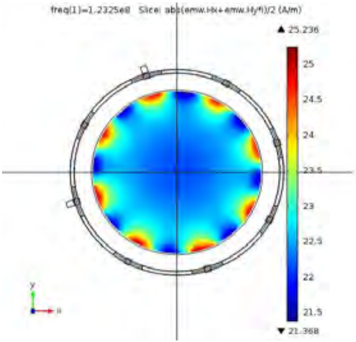


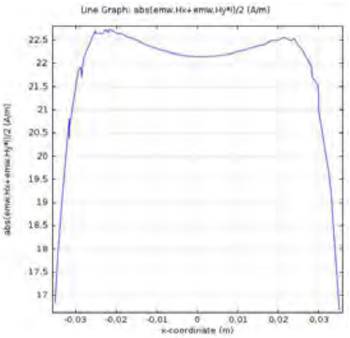
Simulation Results - 1st Scenario Unloaded and Unshielded 8-leg Low-pass BC

$\mathbf{H^{+}}$ **uniformity** $\rightarrow$ for quadrature excitation

Simulation Results - 1^{st} Scenario
Unloaded and Unshielded 8-leg Low-pass BC

H^+ **uniformity** $\rightarrow$ for quadrature excitation





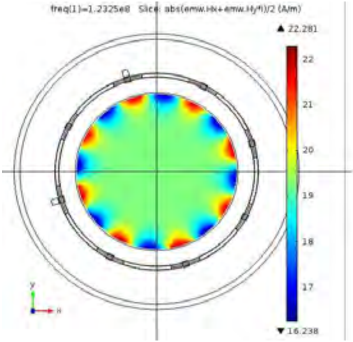
Simulation Results - 2^{nd} Scenario Unloaded and Shielded 8-leg Low-pass BC

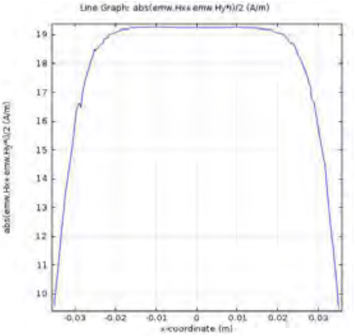
Simulation Results - 2^{nd} Scenario Unloaded and Shielded 8-leg Low-pass BC

$\mathbf{H^{+}}$ **uniformity** $\rightarrow$ for quadrature excitation

Simulation Results - 2^{nd} Scenario Unloaded and Shielded 8-leg Low-pass BC

H$^+$ uniformity $\rightarrow$ for quadrature excitation

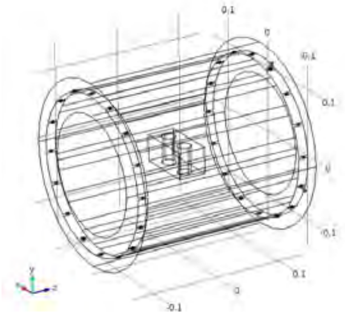


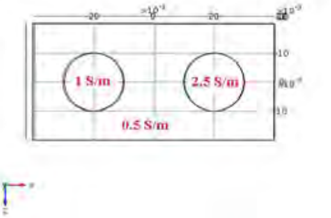


Simulation Results - 3^{rd} Scenario Loaded and Shielded 16-leg High-pass BC

Simulation Results - 3^{rd} Scenario Loaded and Shielded 16-leg High-pass BC

Geometric model



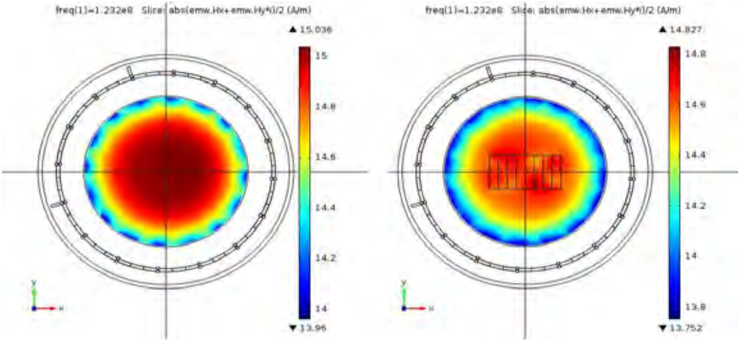


Simulation Results - 3^{rd} Scenario Loaded and Shielded 16-leg High-pass BC

$\mathbf{H}^{+}$ $\rightarrow$ for unloaded and loaded case (quadrature excitation)

Simulation Results - 3^{rd} Scenario
Loaded and Shielded 16-leg High-pass BC

$\mathbf{H}^+ \rightarrow$ for unloaded and loaded case (quadrature excitation)

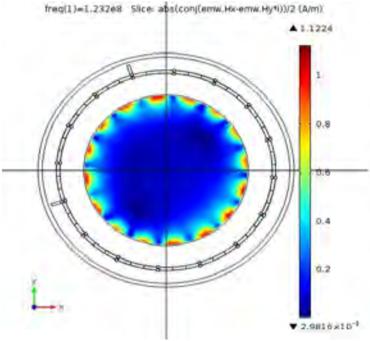


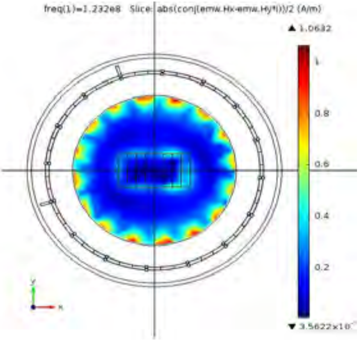
Simulation Results - 3^{rd} Scenario
Loaded and Shielded 16-leg High-pass BC

$\mathbf{H}^{-}$ $\rightarrow$ for unloaded and loaded case (quadrature excitation)

Simulation Results - 3^{rd} Scenario Loaded and Shielded 16-leg High-pass BC

$\mathbf{H}^{-}$ $\rightarrow$ for unloaded and loaded case (quadrature excitation)





Simulation Results - 3^{rd} Scenario
Loaded and Shielded 16-leg High-pass BC

SAR distribution of an object

Simulation Results - 3^{rd} Scenario
Loaded and Shielded 16-leg High-pass BC

SAR distribution of an object

$$SAR = \frac{\sigma |\mathbf{E}|^2}{\rho}$$

σ: conductivity, ρ: density

Simulation Results - 3^{rd} Scenario Loaded and Shielded 16-leg High-pass BC

SAR distribution of an object

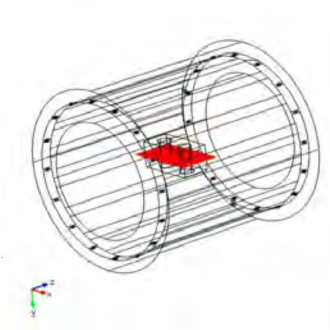
$$SAR = \frac{\sigma |\mathbf{E}|^2}{\rho}$$

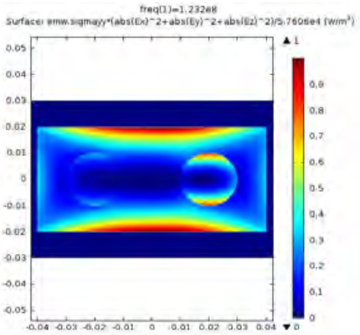
σ: conductivity, ρ: density

Normalized SAR distribution $\rightarrow$ for quadrature excitation

Simulation Results - 3^{rd} Scenario Loaded and Shielded 16-leg High-pass BC

Normalized SAR distribution $\rightarrow$ for quadrature excitation





Outline

1. Introduction
   - RF coils in MRI
   - RF birdcage coils
   - Design and simulation of RF birdcage coils
2. Motivation
   - Review of previous studies
   - Problem definition
   - Our work
3. Methods
   - FEM Models of Birdcage Coils
   - Frequency Domain Analysis
   - Eigenfrequency Analysis
   - Software Tool
4. Experimental Results
5. Conclusion

Resonant Mode Analysis of a Birdcage Coil

Resonant Mode Analysis of a Birdcage Coil

calculates the resonant modes of the birdcage coil

Resonant Mode Analysis of a Birdcage Coil

calculates the resonant modes of the birdcage coil **and the electromagnetic field distributions at these resonant modes**

Resonant Mode Analysis of a Birdcage Coil

calculates the resonant modes of the birdcage coil **and the electromagnetic field distributions at these resonant modes** for the given capacitance value

Eigenfrequency Analysis in COMSOL Multiphysics

Eigenfrequency Analysis in COMSOL Multiphysics

- use developed FEM models of birdcage coils

Eigenfrequency Analysis in COMSOL Multiphysics

- use developed FEM models of birdcage coils
- add eigenfrequency study

Eigenfrequency Analysis in COMSOL Multiphysics

- use developed FEM models of birdcage coils
- add eigenfrequency study
  - specify number of eigenfrequencies

Eigenfrequency Analysis in COMSOL Multiphysics

- use developed FEM models of birdcage coils
- add eigenfrequency study
  - specify number of eigenfrequencies
  - specify a frequency point
- add eigenvalue solver

Eigenfrequency Analysis in COMSOL Multiphysics

- use developed FEM models of birdcage coils
- add eigenfrequency study
    - specify number of eigenfrequencies
    - specify a frequency point
- add eigenvalue solver
    - change the linearization point (if necessary)

Simulation Results

Simulation Results

two different scenarios;

Simulation Results

two different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil

Simulation Results

two different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 16-leg high-pass birdcage coil

Simulation Results

two different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 16-leg high-pass birdcage coil

observed electromagnetic variables

Simulation Results

two different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 16-leg high-pass birdcage coil

observed electromagnetic variables

- H^+ at these resonant modes

Simulation Results

two different scenarios;

- unloaded and unshielded 8-leg low-pass birdcage coil
- unloaded and shielded 16-leg high-pass birdcage coil

observed electromagnetic variables

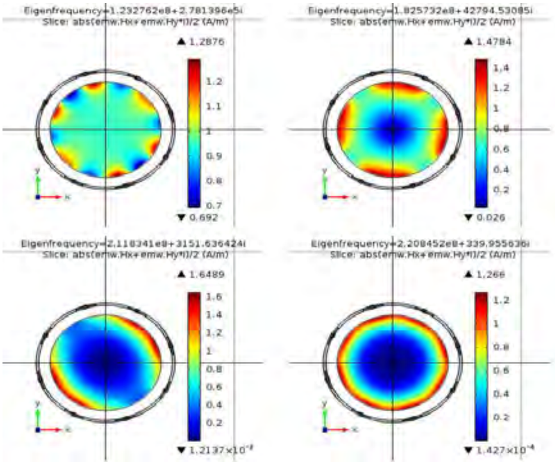
- H^+ at these resonant modes
- surface current density

Simulation Results - 1^{st} Scenario
Unloaded and Unshielded 8-leg Low-pass BC

Simulation Results - 1^{st} Scenario Unloaded and Unshielded 8-leg Low-pass BC

$\mathbf{H}^{+} \rightarrow$ for all resonant modes

Simulation Results - 1^{st} Scenario Unloaded and Unshielded 8-leg Low-pass BC



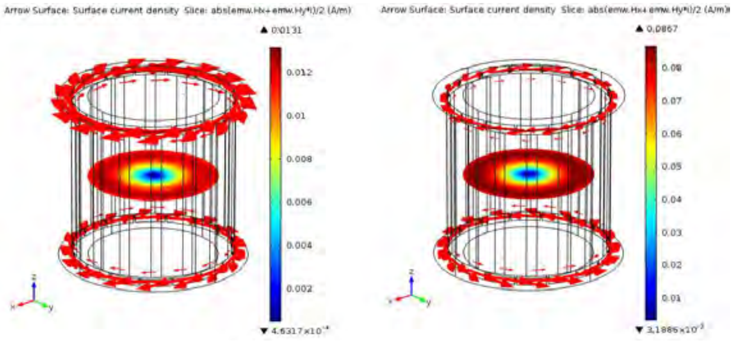
Simulation Results - 2^{nd} Scenario Unloaded and shielded 16-leg High-pass BC

Simulation Results - 2^{nd} Scenario
Unloaded and shielded 16-leg High-pass BC

H^{+} and **surface current densities** $\rightarrow$ for m=0 mode

Simulation Results - 2^{nd} Scenario
Unloaded and shielded 16-leg High-pass BC

H$^+$ and **surface current densities** $\rightarrow$ for m=0 mode



Outline

Software Tool for Designing and Simulating a Birdcage Coil

Software Tool for Designing and Simulating a Birdcage Coil

PURPOSE:

Software Tool for Designing and Simulating a Birdcage Coil

PURPOSE:

- To provide convenience for the coil designers and the researchers in the field of MRI

Software Tool for Designing and Simulating a Birdcage Coil

PURPOSE:

- To provide convenience for the coil designers and the researchers in the field of MRI to use the proposed simulation methods easily and according to the parameters they specify

Software Tool for Designing and Simulating a Birdcage Coil

PURPOSE:

- To provide convenience for the coil designers and the researchers in the field of MRI to use the proposed simulation methods easily and according to the parameters they specify

developed software tool

Software Tool for Designing and Simulating a Birdcage Coil

PURPOSE:

- To provide convenience for the coil designers and the researchers in the field of MRI to use the proposed simulation methods easily and according to the parameters they specify

developed software tool

- FEM based Frequency Domain and Eigenfrequency Analysis Tool (FEM-FDA-EFAT)

Properties of the sofware tool

Properties of the sofware tool

- developed in MATLAB

Properties of the sofware tool

- developed in MATLAB
- has graphical-user-interface (GUI)

Properties of the sofware tool

- developed in MATLAB
- has graphical-user-interface (GUI)
- makes all design and simulation steps according to the user-specified parameters by connecting to the COMSOL Multiphysics server

Properties of the sofware tool

- developed in MATLAB
- has graphical-user-interface (GUI)
- makes all design and simulation steps according to the user-specified parameters by connecting to the COMSOL Multiphysics server
  - modeling the coil geometry

Properties of the sofware tool

- developed in MATLAB
- has graphical-user-interface (GUI)
- makes all design and simulation steps according to the user-specified parameters by connecting to the COMSOL Multiphysics server
  - modeling the coil geometry
  - adding physics and boundary condition

Properties of the sofware tool

- developed in MATLAB
- has graphical-user-interface (GUI)
- makes all design and simulation steps according to the user-specified parameters by connecting to the COMSOL Multiphysics server
  - modeling the coil geometry
  - adding physics and boundary condition
  - generating mesh for the model

Properties of the sofware tool

- developed in MATLAB
- has graphical-user-interface (GUI)
- makes all design and simulation steps according to the user-specified parameters by connecting to the COMSOL Multiphysics server
  - modeling the coil geometry
  - adding physics and boundary condition
  - generating mesh for the model
  - adding study and solver sequence

Properties of the sofware tool

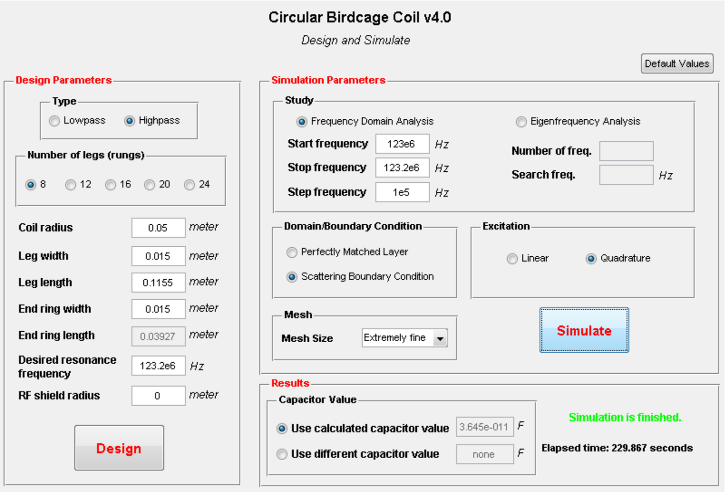
- developed in MATLAB
- has graphical-user-interface (GUI)
- makes all design and simulation steps according to the user-specified parameters by connecting to the COMSOL Multiphysics server
  - modeling the coil geometry
  - adding physics and boundary condition
  - generating mesh for the model
  - adding study and solver sequence
  - computing the solutions

Properties of the sofware tool

- developed in MATLAB
- has graphical-user-interface (GUI)
- makes all design and simulation steps according to the user-specified parameters by connecting to the COMSOL Multiphysics server
  - modeling the coil geometry
  - adding physics and boundary condition
  - generating mesh for the model
  - adding study and solver sequence
  - computing the solutions
- when the computation is finished, results can be observed in COMSOL Multiphysics

FEM-FDA-EFAT

FEM-FDA-EFAT


Circular Birdcage Coil v4.0
Design and Simulate
Default Values
Design Parameters
Type
Lowpass
Highpass
Number of legs (rungs)
8
12
16
20
24
Coil radius
0.05
meter
Leg width
0.015
meter
Leg length
0.1155
meter
End ring width
0.015
meter
End ring length
0.03927
meter
Desired resonance frequency
123.2e6
Hz
RF shield radius
0
meter
Design
Simulation Parameters
Study
Frequency Domain Analysis
Eigenfrequency Analysis
Start frequency
123e6
Hz
Stop frequency
123.2e6
Hz
Step frequency
1e5
Hz
Number of freq.
Search freq.
Hz
Domain/Boundary Condition
Perfectly Matched Layer
Scattering Boundary Condition
Excitation
Linear
Quadrature
Mesh
Mesh Size
Extremely fine
Simulate
Results
Capacitor Value
Use calculated capacitor value
3.645e-011
F
Use different capacitor value
none
F
Simulation is finished.
Elapsed time: 229.867 seconds

Outline

Handmade Low-pass Birdcage Coil

Handmade Low-pass Birdcage Coil

- 8-leg low-pass birdcage coil is constructed on plexiglass tube

Handmade Low-pass Birdcage Coil

Experimental Results and Comparison with Numerical Analyses

for the resonant modes

Experimental Results and Comparison with Numerical Analyses

for the resonant modes

Experimental Results and Comparison with Numerical Analyses

for the resonant modes

- S_{11} of the coil for five different capacitance values

Experimental Results and Comparison with Numerical Analyses

for the resonant modes

- S_{11} of the coil for five different capacitance values
- compare the measured resonant modes

Experimental Results and Comparison with Numerical Analyses

for the resonant modes

- S_{11} of the coil for five different capacitance values
- compare the measured resonant modes
  - Jin's software tool, `MRIEM`

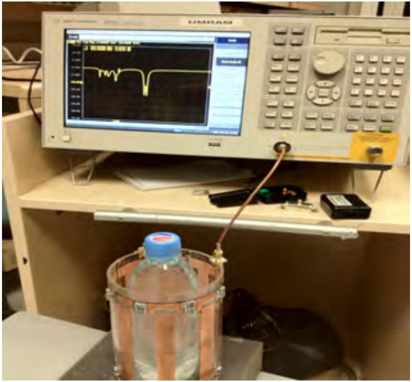
Experimental Results and Comparison with Numerical Analyses

for the resonant modes

- S_{11} of the coil for five different capacitance values
- compare the measured resonant modes
  - Jin's software tool, `MRIEM`
  - Our software tool, `FEM-EFAT`

Experimental Results and Comparison with Numerical Analyses

Experimental Results and Comparison with Numerical Analyses



Measured and Calculated Resonant Modes Results for Low-pass Birdcage Coil

Measured and Calculated Resonant Modes Results for Low-pass Birdcage Coil

used capacitance values

47 pF, 10 pF, 3.3 pF, 1.8 pF, 1 pF

Measured and Calculated Resonant Modes Results for Low-pass Birdcage Coil

Results for 47pF

Modes	Measured (MHz)	MRIEM (MHz)	FEM-EFAT (MHz)
m=1	60.75	67.46	59.1
m=2	85.88	90.64	87.22
m=3	93.38	102.2	101.1
m=4	102.8	-	105.4

Measured and Calculated Resonant Modes Results for Low-pass Birdcage Coil

Results for 10pF

Modes	Measured (MHz)	MRIEM (MHz)	FEM-EFAT (MHz)
m=1	122.11	146.25	124.76
m=2	196.48	196.51	184.80
m=3	208.54	221.57	214.41
m=4	214.97	-	223.54

Measured and Calculated Resonant Modes Results for Low-pass Birdcage Coil

Results for 3.3pF

Modes	Measured (MHz)	MRIEM (MHz)	FEM-EFAT (MHz)
m=1	211.3	254.59	205.37
m=2	306.3	342.08	306.62
m=3	330.0	385.71	356.47
m=4	345.0	-	371.75

Measured and Calculated Resonant Modes Results for Low-pass Birdcage Coil

Results for 1.8pF

Modes	Measured (MHz)	MRIEM (MHz)	FEM-EFAT (MHz)
m=1	255.2	344.71	260.62
m=2	382.0	463.19	392.18
m=3	417.0	522.26	456.8
m=4	441.5	-	476.5

Measured and Calculated Resonant Modes Results for Low-pass Birdcage Coil

Results for 1pF

Modes	Measured (MHz)	MRIEM (MHz)	FEM-EFAT (MHz)
m=1	335.7	462.48	316.85
m=2	473.1	621.42	481.6
m=3	512.3	700.68	562.24
m=4	525.9	-	586.63

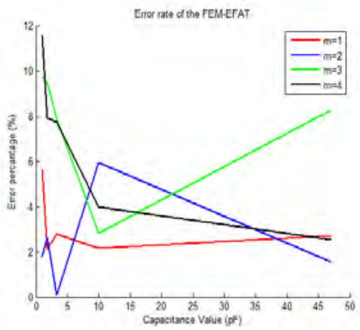
Measured and Calculated Resonant Modes Results for Low-pass Birdcage Coil

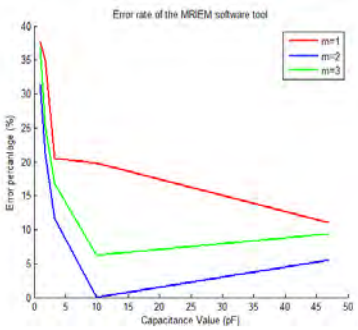
Percentage error

$$Error\ rate\ (\%) = 100 \times \left| \frac{f_{meas} - f_{calc}}{f_{meas}} \right|$$

Measured and Calculated Resonant Modes Results for Low-pass Birdcage Coil

Percentage error rate for FEM-EFAT and MRIEM





Outline

Conclusion

Conclusion

We have proposed two FEM based simulation methods using **developed FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics:

Conclusion

We have proposed two FEM based simulation methods using **developed FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics:

- Frequency Domain Analysis

Conclusion

We have proposed two FEM based simulation methods using **developed FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics:

- Frequency Domain Analysis
  - electromagnetic fields solutions of a birdcage coil for any scenario

Conclusion

We have proposed two FEM based simulation methods using **developed FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics:

- Frequency Domain Analysis
  - electromagnetic fields solutions of a birdcage coil for any scenario
- Eigenfrequency Analysis

Conclusion

We have proposed two FEM based simulation methods using **developed FEM models of low-pass and high-pass birdcage coils** in COMSOL Multiphysics:

- Frequency Domain Analysis
  - electromagnetic fields solutions of a birdcage coil for any scenario
- Eigenfrequency Analysis
  - resonant modes of a birdcage coil and electromagnetic field solutions at these resonant modes

Conclusion

Conclusion

- A software tool is developed to make these two simulation methods easily and according to the user-specified parameters

Conclusion

- A software tool is developed to make these two simulation methods easily and according to the user-specified parameters
- Experimental results show that results of the proposed software tool is more accurate than the results of software tool which uses lumped circuit element model

Conclusion

- A software tool is developed to make these two simulation methods easily and according to the user-specified parameters
- Experimental results show that results of the proposed software tool is more accurate than the results of software tool which uses lumped circuit element model
- These methods can be adapted to design and simulate other MRI RF coils

One more thing...

One more thing...