Electromagnetic Acoustic MRT Simulation

Development of a Digital Twin

Joint Presentation by:

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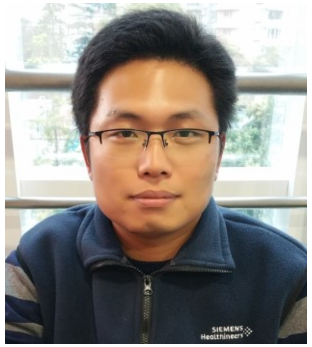
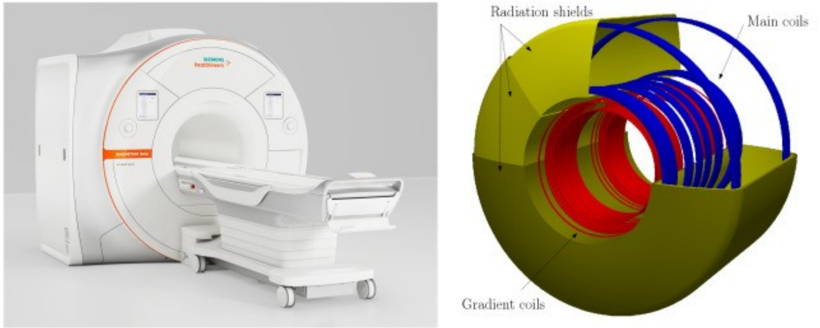
Zong Fang Chen, Siemens Shenzhen Magnetic Resonance Ltd, China, (Siemens-Healthineers)

Karlsruhe, 21.11.2023,

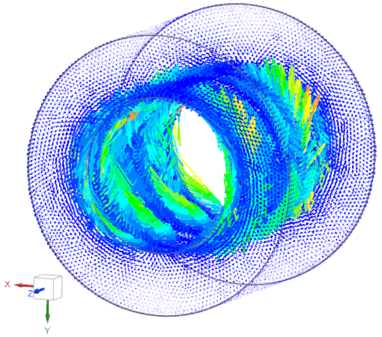
PLM-Benutzergruppe –

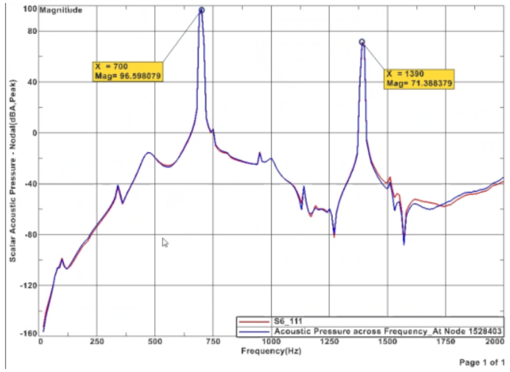
SIG Simulation





(a) MRI model MAGNETOM Sola 1.5 T, courtesy of Siemens Healthineers. (b) Simplified MRI showing the three main components: main coils, gradient coils and radiation shields.





Content

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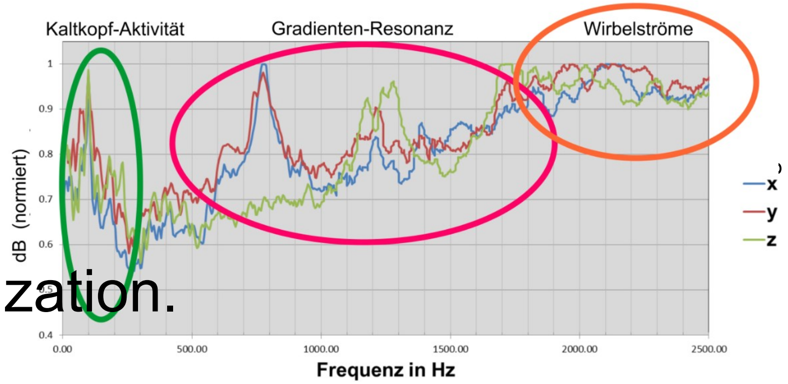
1. Introduction, Motivation



The noise level in an MRI is high and unpleasant for the patient.

Acoustic measurements are time-consuming and inflexible.

A simulation model is therefore to be developed for future optimization.

The model must simulate the electromagnetic fields of the main components and convert them into mechanical forces. These are then used as excitation in an acoustic simulation.

The model must be calibrated with measurement results at arbitrary positions. The deviations of the first two peaks should not be greater than a limit value.

The finished model is handed over to the customer as a Simcenter data set. Special training and further support ensure success.

What is new about this work is the complete 3D FEM simulation of both the electromagnetic and the acoustic system. High accuracy and high detailing is therefore possible.

MRI (Nuclear Magnetic Resonance; NMR) is often referred to as magnetic resonance imaging or nuclear spin for short. It is an imaging procedure for examining the internal organs.

2. MRT Key Components

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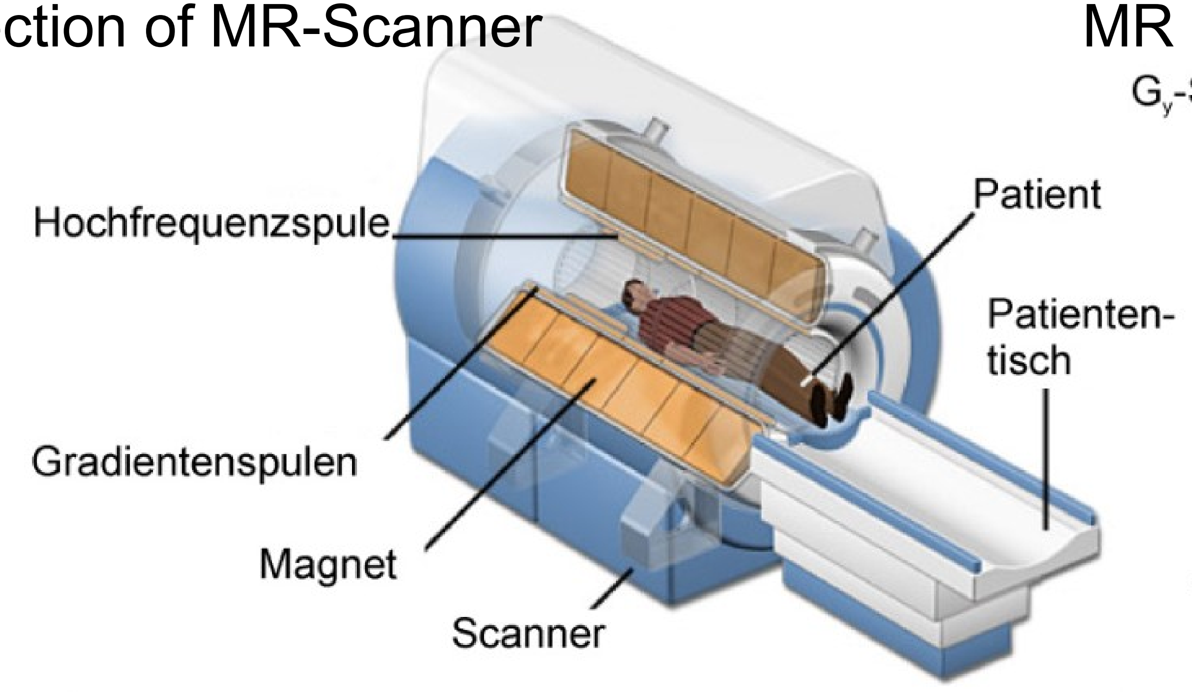
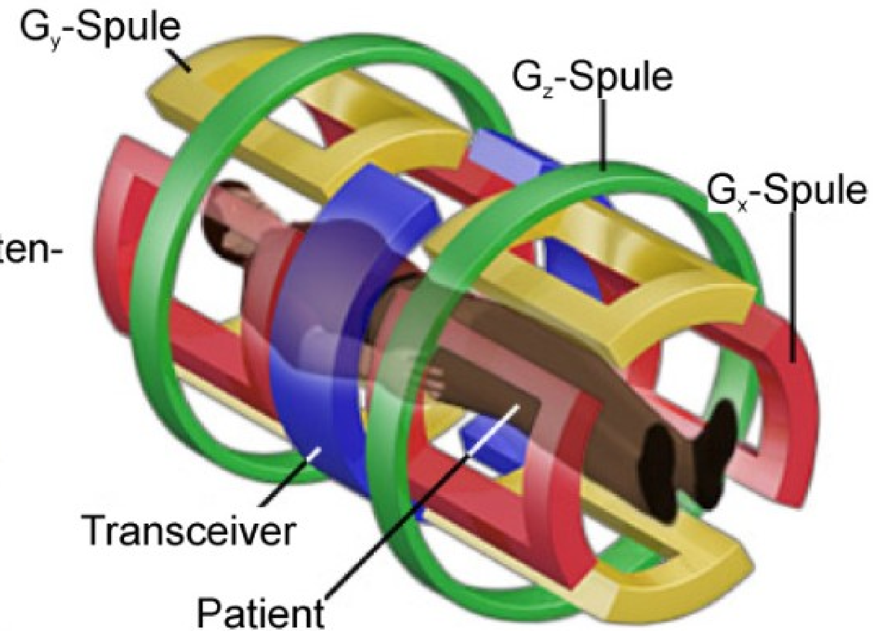
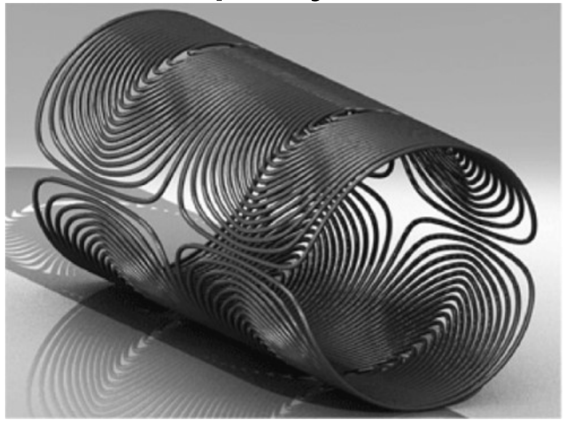
Section of MR-Scanner



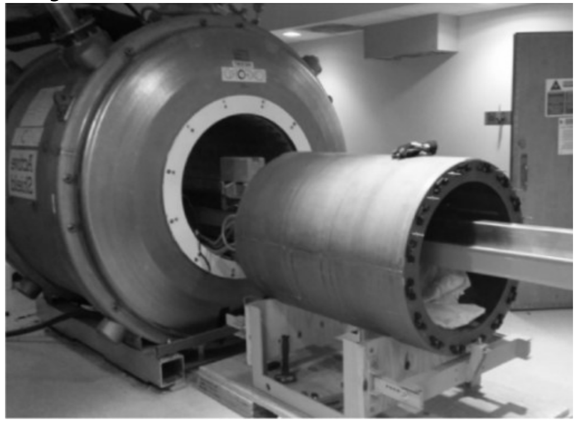
MR Gradientsystem



Gradient-coil without epoxy-resin



Gradientsystem in front of the magnet

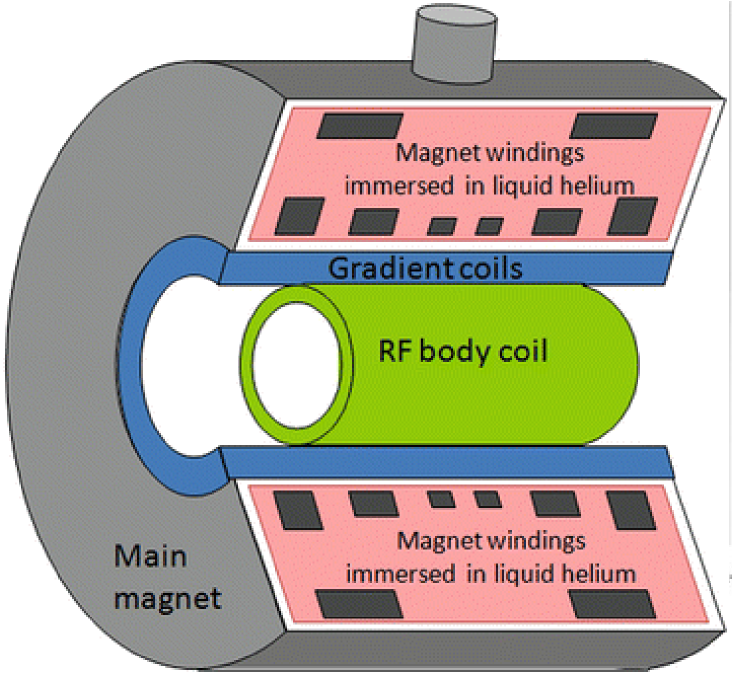


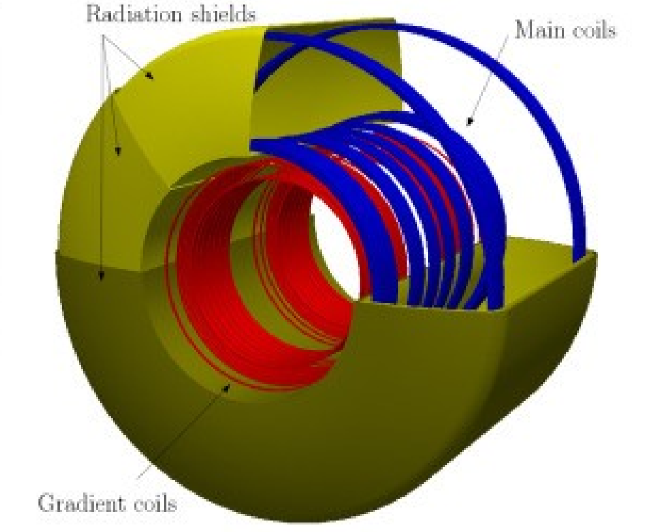
images: [Ott]

3. MRT Key Components, Lorentzforces

Important for acoustics:

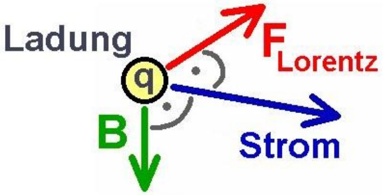
- Gradient coils (x,y,z)
- Main magnet windings
- Housing





(b) Simplified MRI showing the three main components: main coils, gradient coils and radiation shields.

Lorentz forces



- ***F*** = vector cross product of electric current ***I*** and magnetic flux density ***B***
- arises on the x,y,z coils at each point
- arises indirectly in the housing due to induced eddy currents

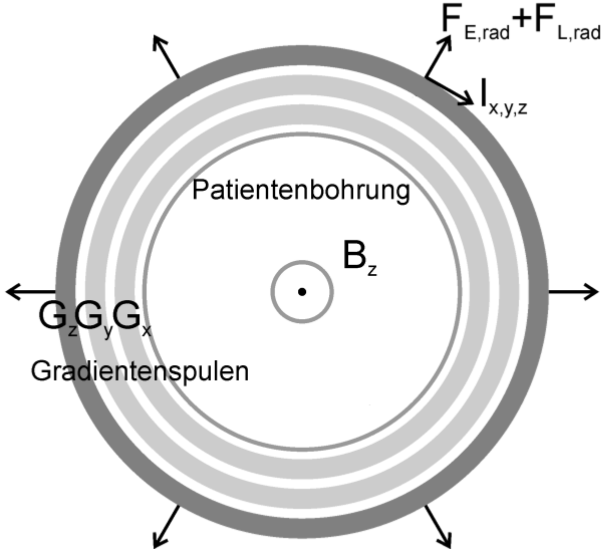


image: [RadiologyKey]

4. Lorentz forces of x,y,z coils and sound generation

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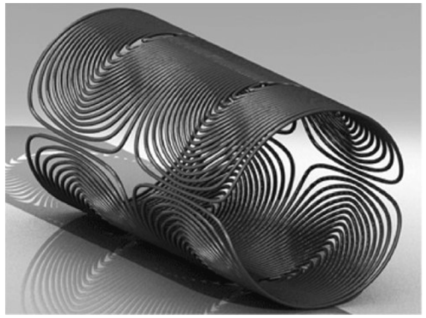
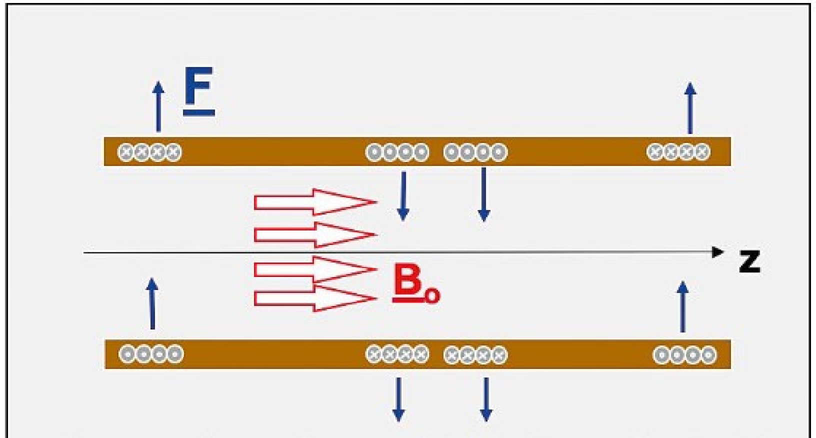
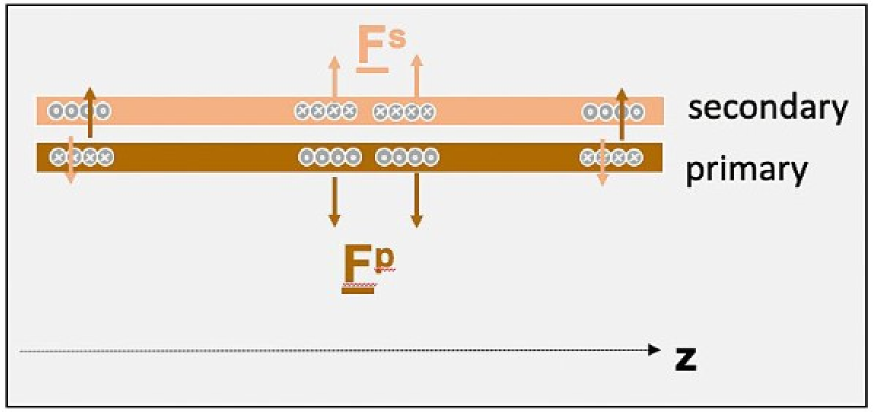
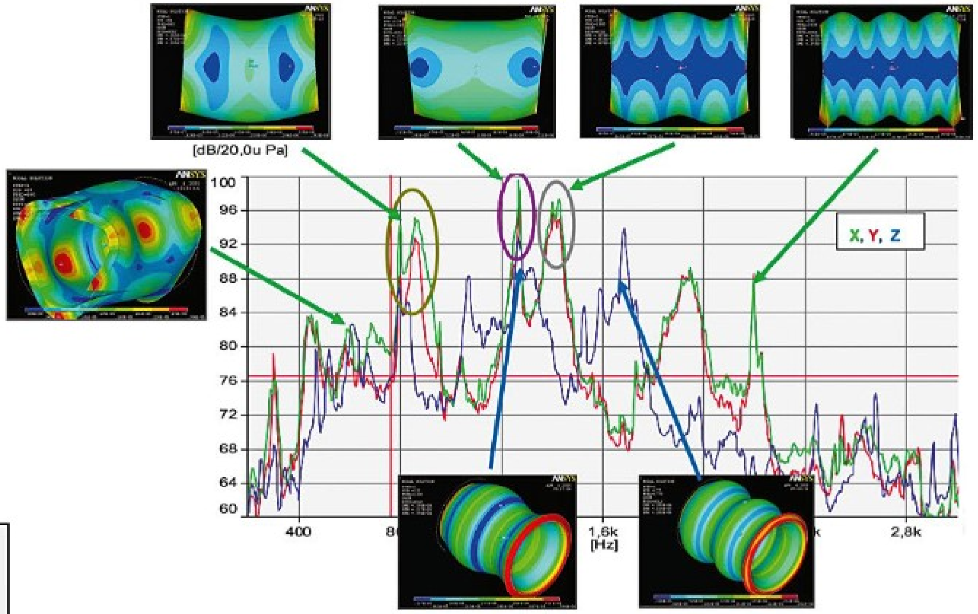
Depending on the direction of the coil winding, Lorentz forces arise in different directions.
Difficult to predict due to geometric complexity - simulation required!



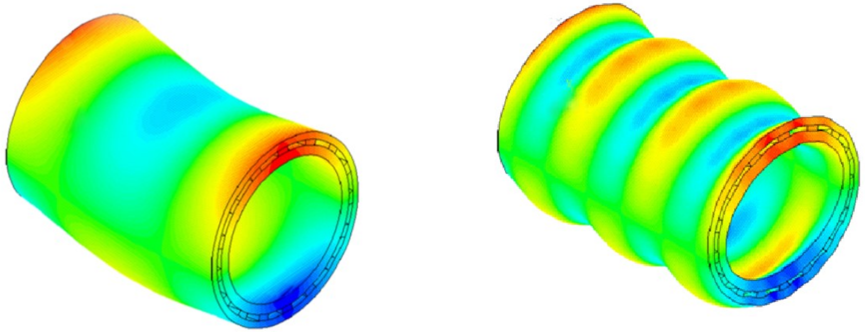


Cross section of an unshielded Y gradient coil





Typical geometric vibration modes



images: [Schmitt], [Ott]

5. Gradient Coil Wires

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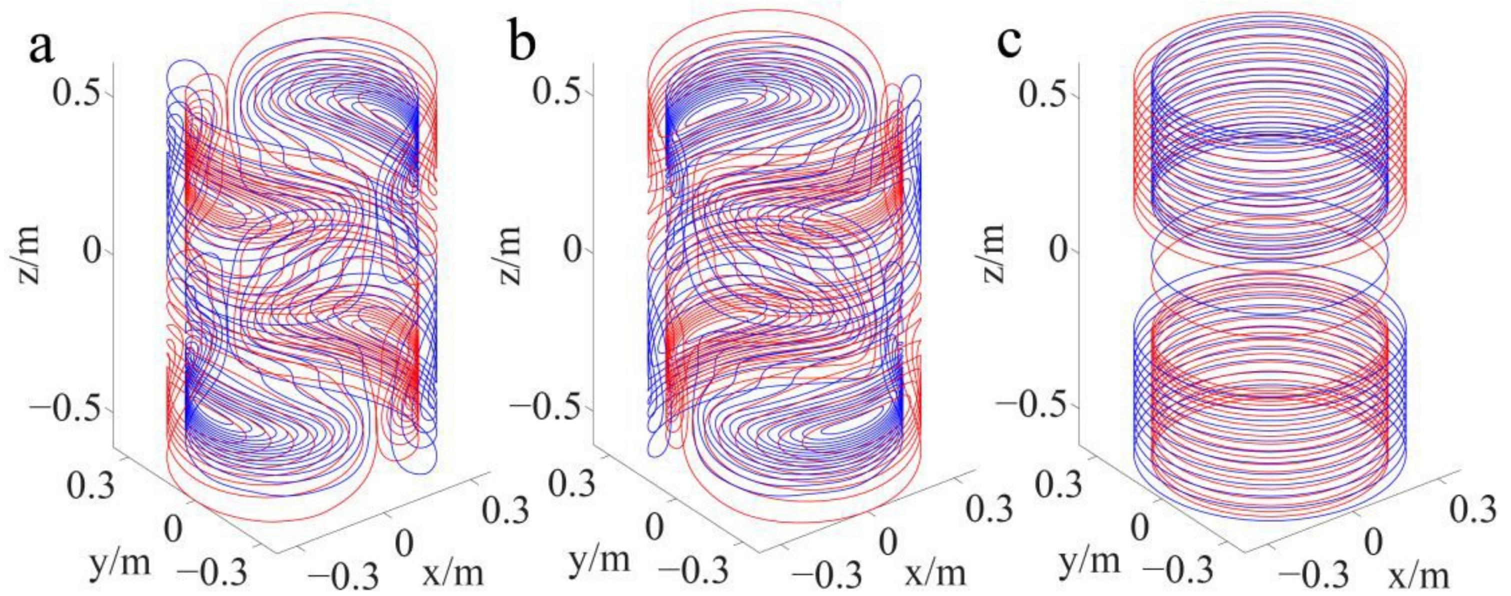
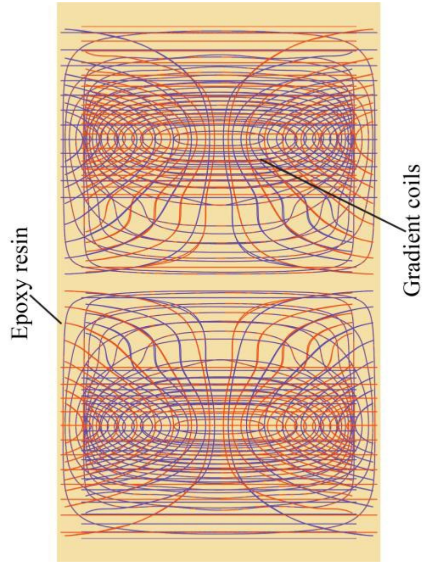
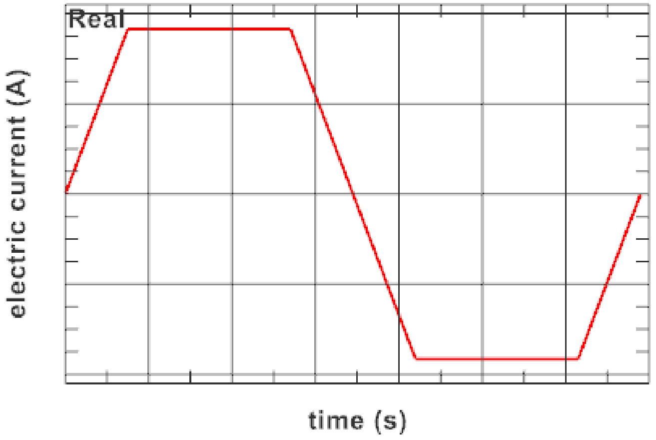
Three coil systems X,Y,Z generate the gradient fields required for the process.

Simplified images:





An alternating current signal with a basic frequency of approx. 700 Hz excites the coils.

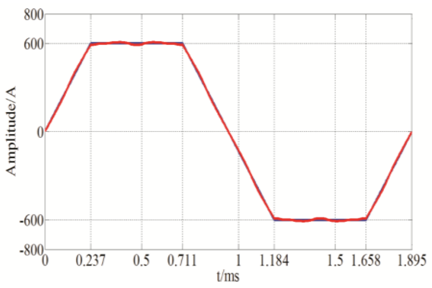


8. Eddy currents and their Lorentz forces

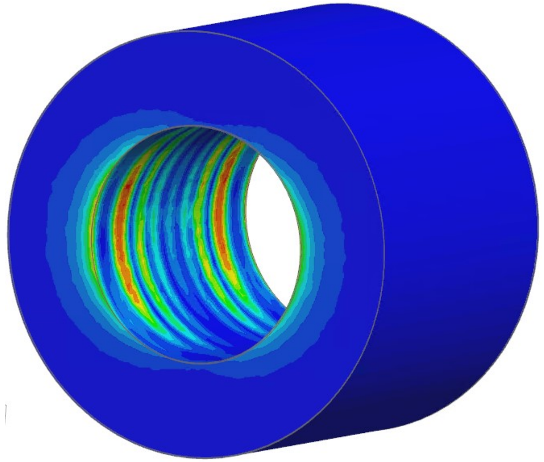
In addition, the switching of gradients leads to time-varying magnetic fields in the environment. This change in the magnetic flux in conductive parts of the MRI system leads to the induction of eddy currents (Faraday's law). The induced eddy currents generate an additional Lorentz force due to the magnetic field.

There are therefore two causes of Lorentz forces: these are the radial Lorentz forces due to the gradient currents and the Lorentz forces due to induced eddy currents.

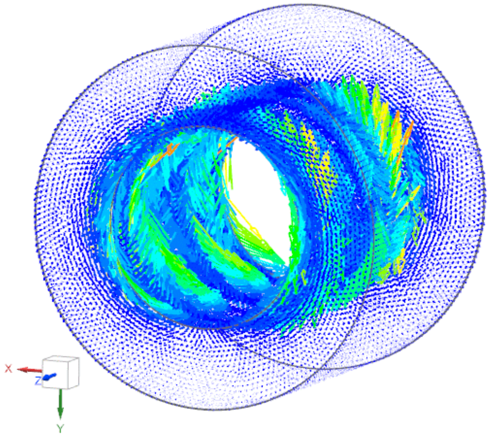
In the first approach, the eddy currents were neglected in the simulation. This is also possible for the first volume peak. For the second, however, it is no longer possible.



Coil current



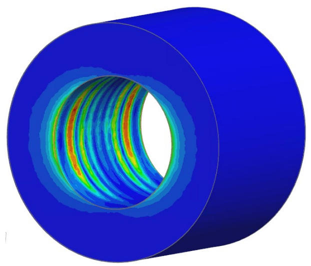
Eddy currents due to X-coil excitation



Lorentz forces due to X-eddy currents

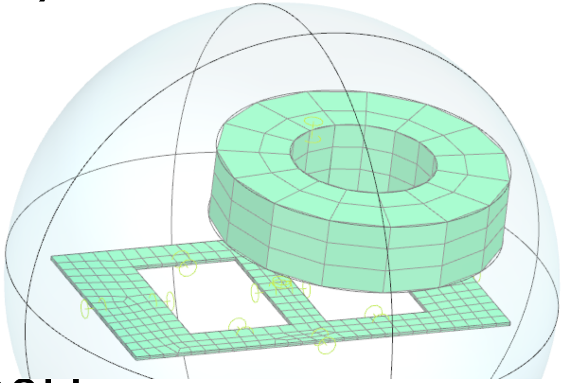
7. Effect of frequency doubling

The Lorentz forces on the housing are doubled in frequency.

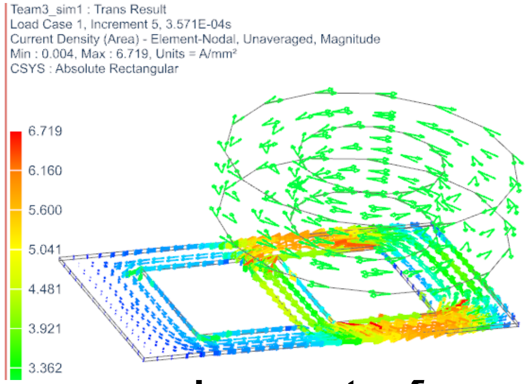


Example of principle: AC coil with aluminum plate, transient simulation

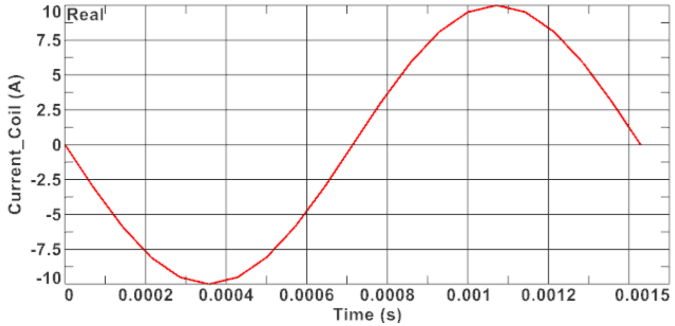
Geometry and FE mesh



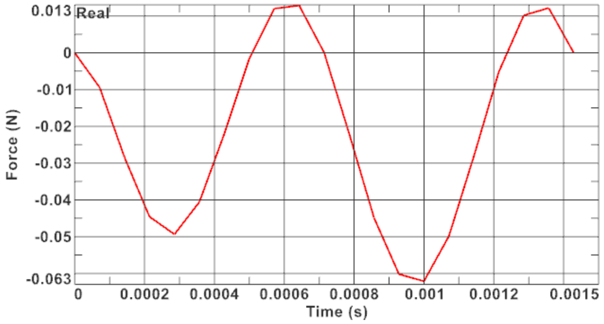
induced currents on plate



Coil current, 700Hz



Lorentz force on plate shows double freq. and transient response



Reason: 90 degree phase shift of the induced current (Faraday) and ***F*** = Cross[***I*** , ***B***]

This must be correctly taken into account in all frequency-domain simulations!

8. Acoustic measurement

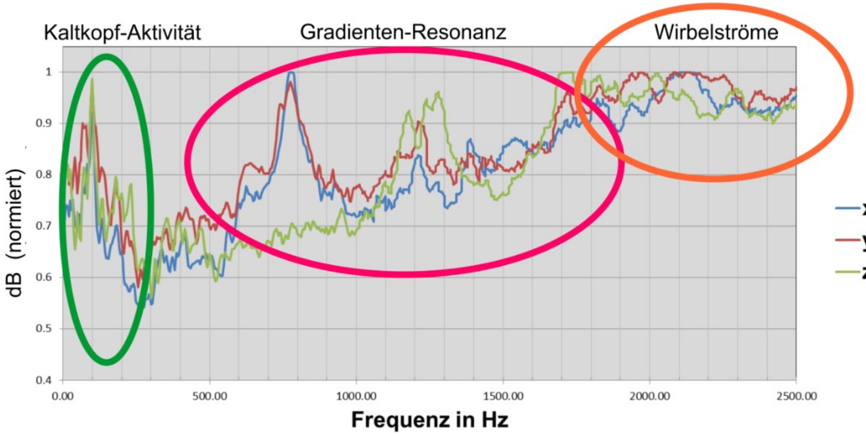
The volume was measured at 5 different positions in the MRT. In each case separately for the X, Y and Z coil excitation.

This results in 15 spectra, in which 2 peaks always appear at approx. 700 and 1400 Hz. So there are 30 numerical values that are compared with the simulation.

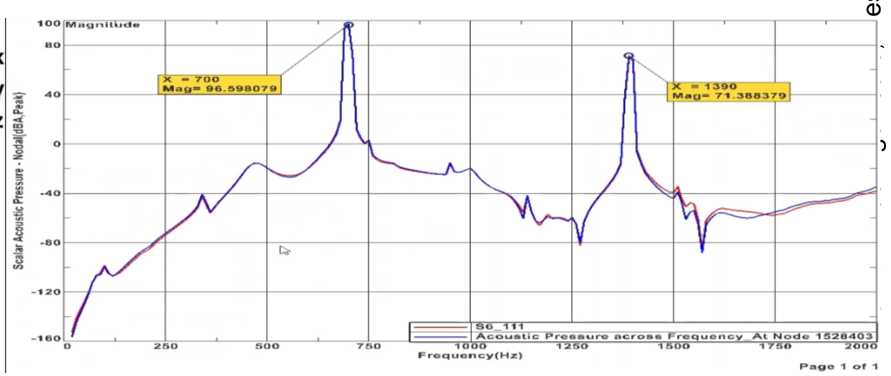
The differences must all be smaller than a limit value for the simulation to be accepted.

Measurement setup

Typical measurement result [Ott]



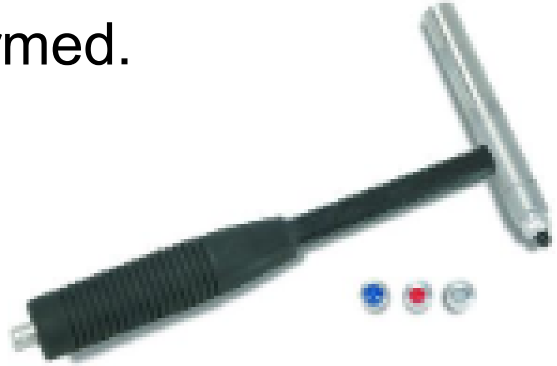
Typical simulation result



9. Measurement of the eigenmodes of the gradient coil

The material properties <u>density and modulus of elasticity</u> have a major influence on the result of the acoustic simulation. The stiffness of connecting parts and the installation also have an impact. To gain more clarity about these parameters, the eigenmodes of the gradient coil were measured.

The simulation model was calibrated to these measured eigenmodes. I.e. Nastran Solutions 103 at different modulus of elasticity, density, etc. were performed.



10. Requirements for the project

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1. Simulate the Lorenz force on X Y and Z coil wires caused by Magnet coils

Perform a transient magnetic simulation with 1D elements for the CG wires and 3D for the remaining parts.
Main results are the Lorentz forces on the wires

2. Mapping the force to the gradient coil (GC) 3D geometry

Perform a deformation simulation with these forces.
The transient forces would be fourier-transformed into frequency domain for further processing in Nastran

3. Simulate the vibration and acoustic noise of GC

Simulate the vibration and acoustic noise of GC, GC would consider as a whole body with resin casted

4. Compare the noise with real test value

Perform the adaption to match the real test value to achieve within a given dB tolerance.

5. Writing a tutorial for the setup of such a model and technique report for the analysis

6. Training by this tutorial (about the half for magnetics, half for acoustics)

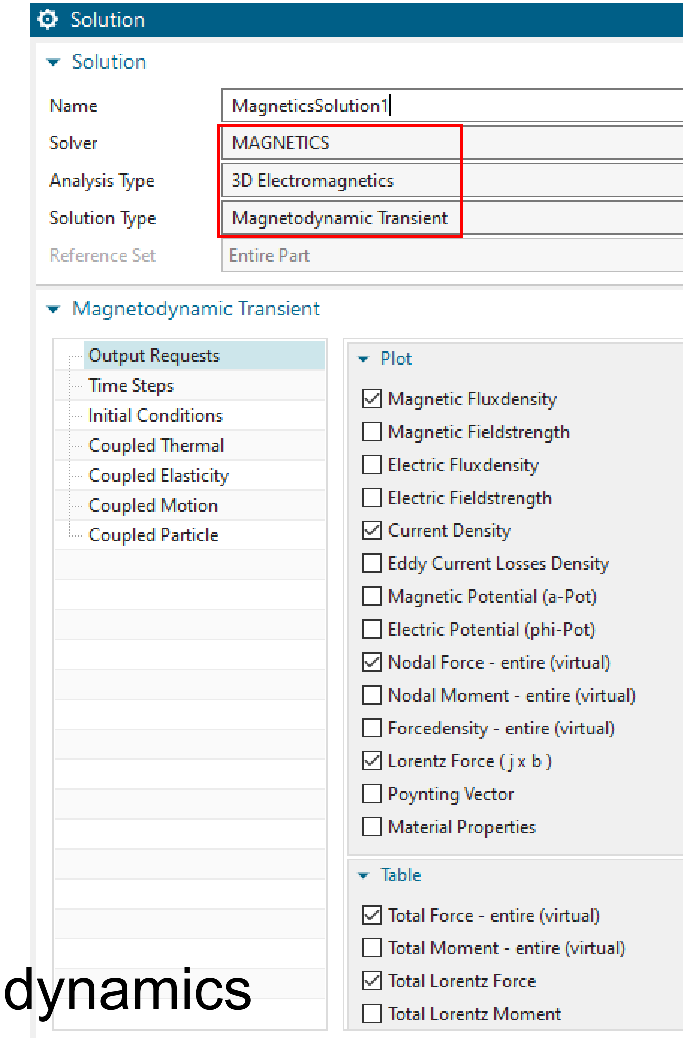
7. Support: technique support until the expert in SSMR understand and repeat all the steps in the simulation

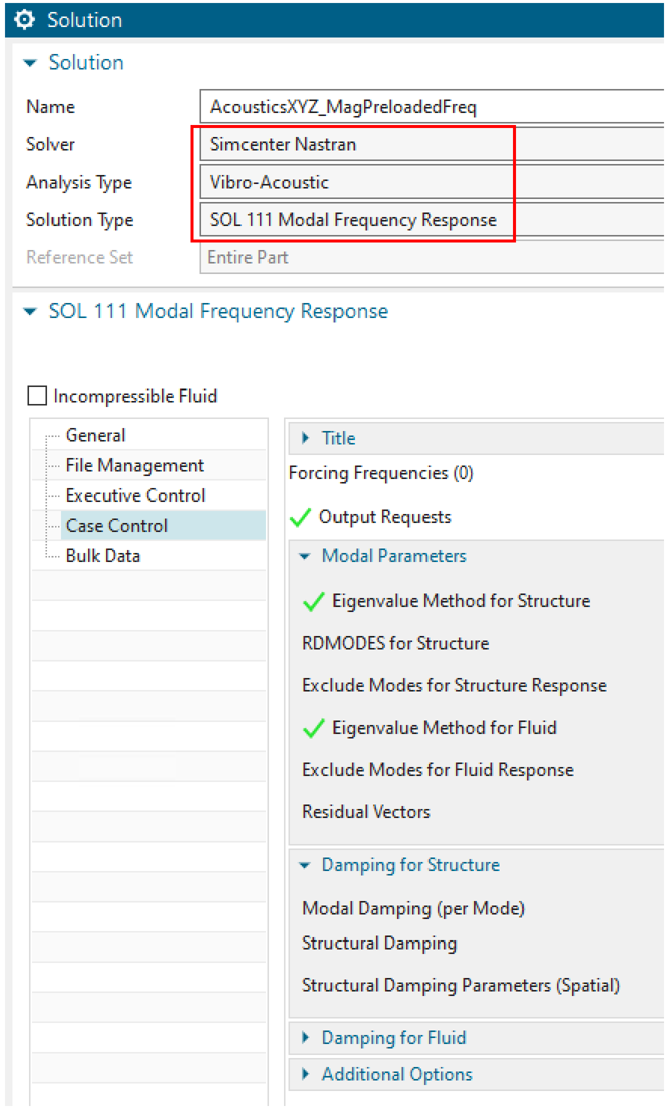
11. Software and solver used

Electromagnetic software: NX-MAGNETICS (Dr. Binde)

Reasons:

- 1D elements possible (coils).
- Integration in Simcenter 3D,
- All frequencies are possible (high/medium/low)
- Customization by software manufacturer easily possible





Acoustic software: SC-NASTRAN

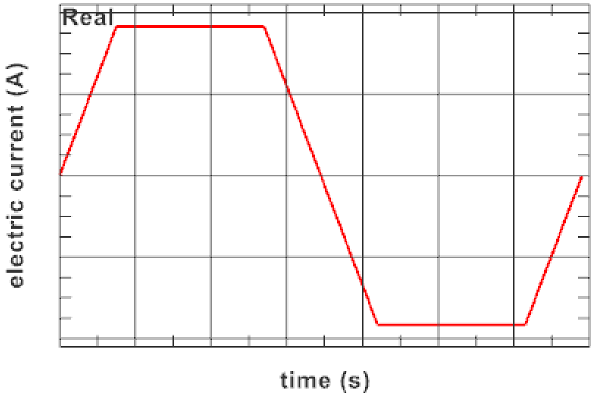
Reasons:

- Best performance in acoustics and dynamics
- Tool of choice at Siemens

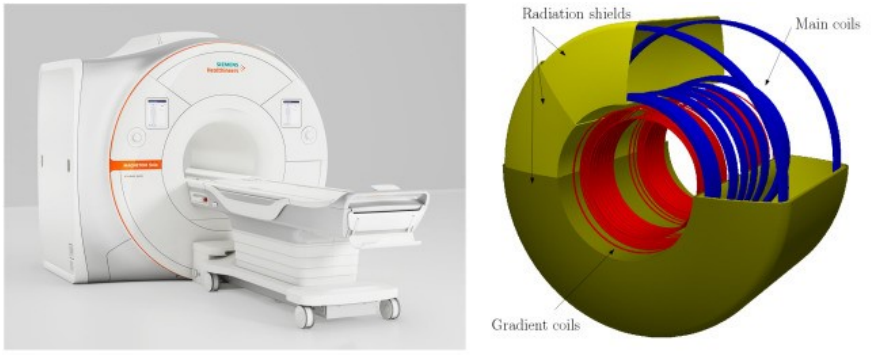
12. Coupling the domains - two possible methods

The domains are coupled by
<u>transferring the electromagnetic forces to the acoustics</u>

1. current signal

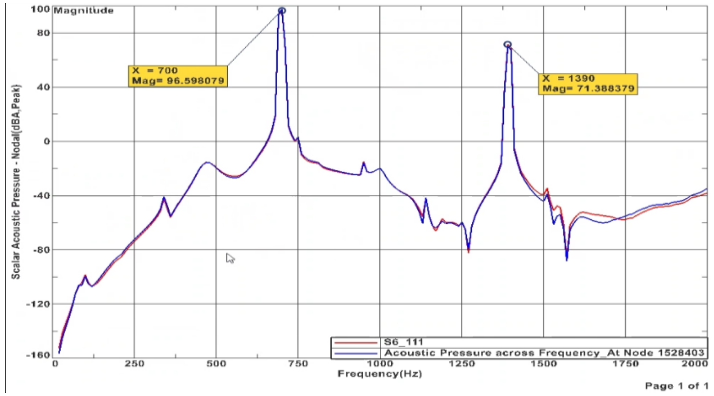


2. simulation model



(a) MRI model MAGNETOM Sola 1.5 T, courtesy of Siemens Healthineers.
(b) Simplified MRI showing the three main components: main coils, gradient coils and radiation shields.

3. acoustic spectrum

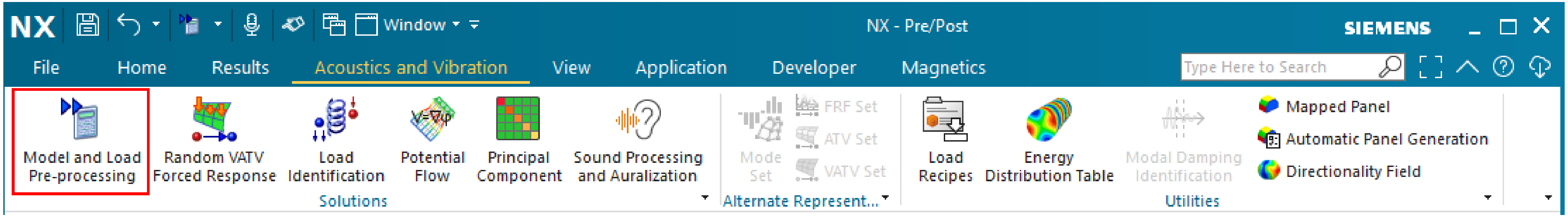


Method 1: Magnetic transient + Fourier + acoustic frequency

Method 2: Magnetic frequency (preloaded) + acoustic frequency

12.1 Magnetics transient + Fourier + Acoustics frequency

1. The electromagnetic simulation is carried out in the time domain. This results in electromagnetic Lorentz forces at each node
2. the Lorentz forces are Fourier-transformed at each node.
   1. For this Fourier transformation, we used a pre-solver tool available in Simcenter 3D called "Model and Load Preprocessing" in combination with an operation called "Time Signal Processing".
   2. This tool reads a result file in unv format with transient nodal forces as output by the Magnetics solver. It performs the Fourier transform for each node and writes out a file in a format that can be used as a load in a Nastran acoustic simulation.
   3. The feature is called from the NX user interface as follows:



3. The acoustic simulation is performed in the frequency domain. The forces are automatically read in by the tool.

12.1 Magnetics transient + Fourier + Acoustics frequency

Advantages of this method

- Safe, because the transient magnetics simulation takes all effects such as non-linearity, doubling of frequencies, reluctance forces, ... into account.
- The tool for the Fourier transformation works very quickly and reliably.

Disadvantages

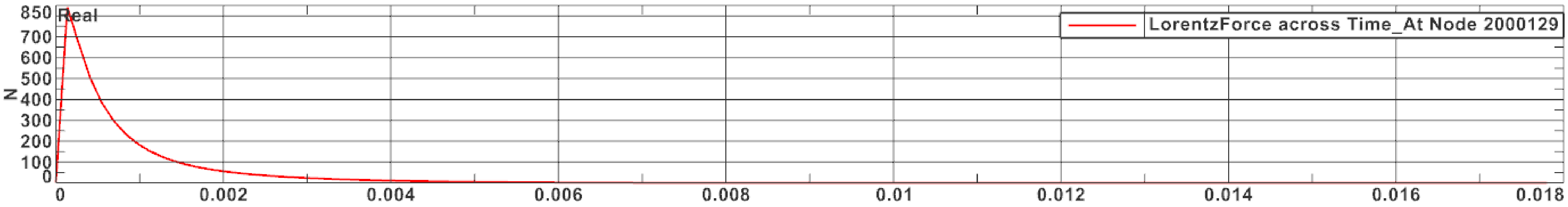
- Complex: It takes a long time to simulate even one period transiently.
- Transient transient effects can possibly lead to large periods (many periods) having to be simulated until the result has settled.

See next page

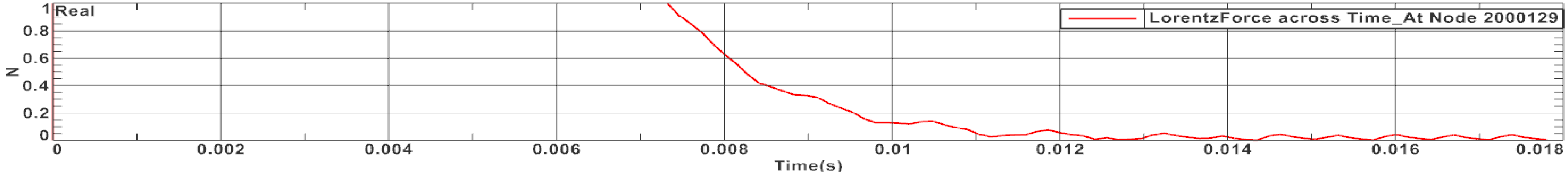
12.1 Magnetics transient + Fourier + Acoustics frequency

- In our simulations, transient effects occurred as soon as the housing was in the model. 13 periods were calculated and the last 3 were used.

Lorentz force curve over 13 periods



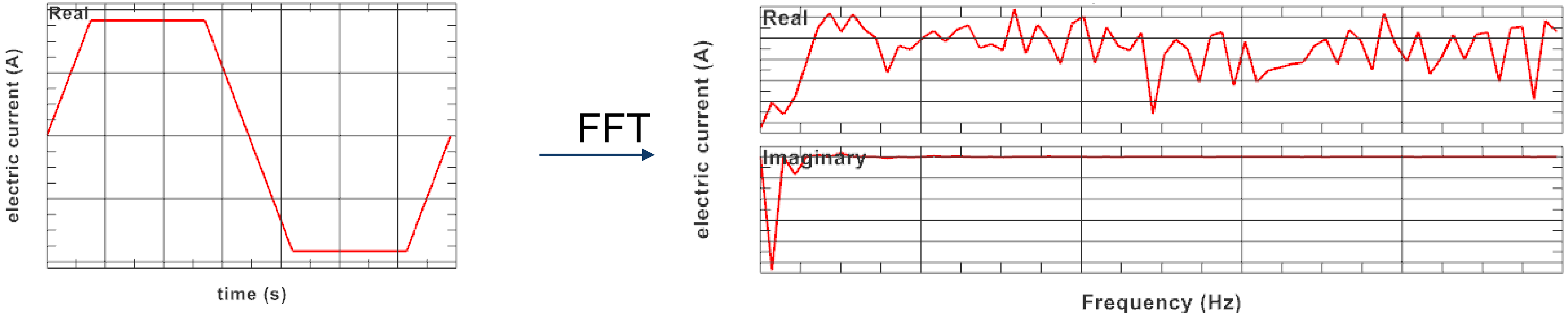
Settled after approx. 10 periods



12.2 Magnetics frequency (preloaded) + Acoustics frequ.

1. Current signal Fourier transformation

   Only the transient current signal is converted into a frequency spectrum by Fourier transformation. This results in the contained frequencies and their respective components. These are quite precisely the frequencies that are also dominant in the measurements.



2. Magnetics simulation

   The magnetic simulation is carried out in the frequency range with the first two of these frequencies. The resulting spatial Lorentz forces (Re/Im) are stored as a node ID field.

3. Acoustic simulation

   The Lorentz forces are applied separately as a force field with Re and Im components.

12.2 Magnetics frequency (preloaded) + Acoustics frequ.

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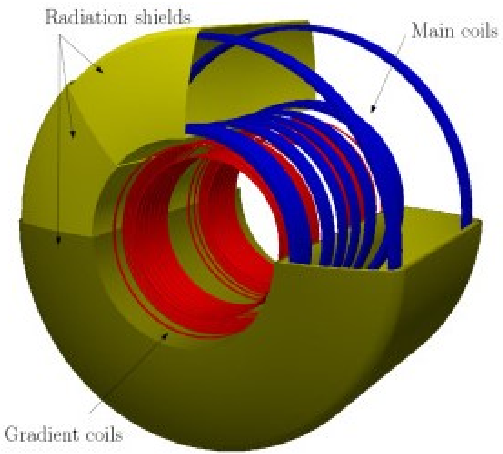


Special features of the magnetic simulation

- In addition, it is necessary to carry out a static pre-calculation in order to take the external magnetic field through the main coils into account. This must be added to the Lorentz forces in the Freq. calculation. A few lines of additional code are inserted into the solver input for this purpose.

Special features of the acoustic simulation

- This method also requires the previously described effect of frequency doubling to be taken into account. This means that the previously calculated Lorentz forces on the housing are applied at twice the frequency in the acoustic model.

Advantages of this method: Magnetics simulation is very fast, only one calculation step is required Transient response: The steady-state result is obtained immediately. This became the method of choice for us.

Disadvantages: The method is more complicated to set up for the first time

13. Magnetics model (simplified representation)

Modellsize

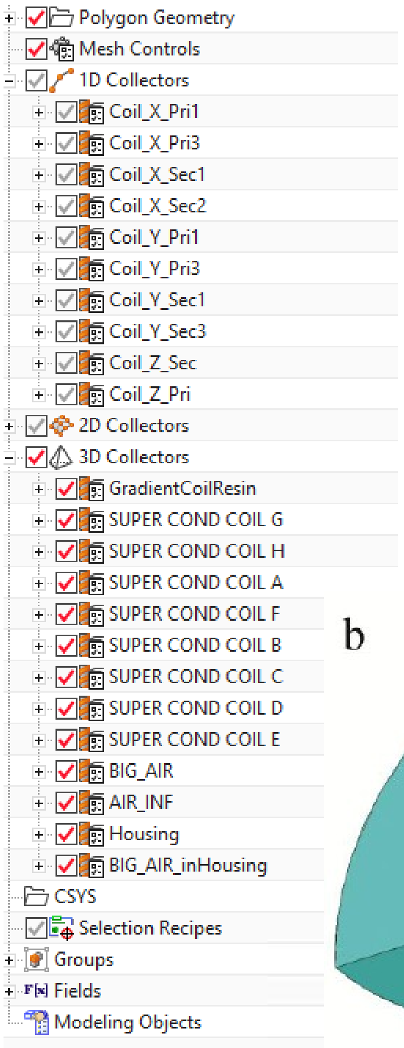
- Elements: 5.185.880 nodes: 768.618 1D Elements: 158.362
- Degrees of freedom: 4.620.322

Challenge:

- Insert many 1D elements in Air inside the 3D mesh (node-to-node)

Computing time:

- 2.5 h (Freq. calculation)
- days (trans. calculation with many periods)



View of a similar model

b

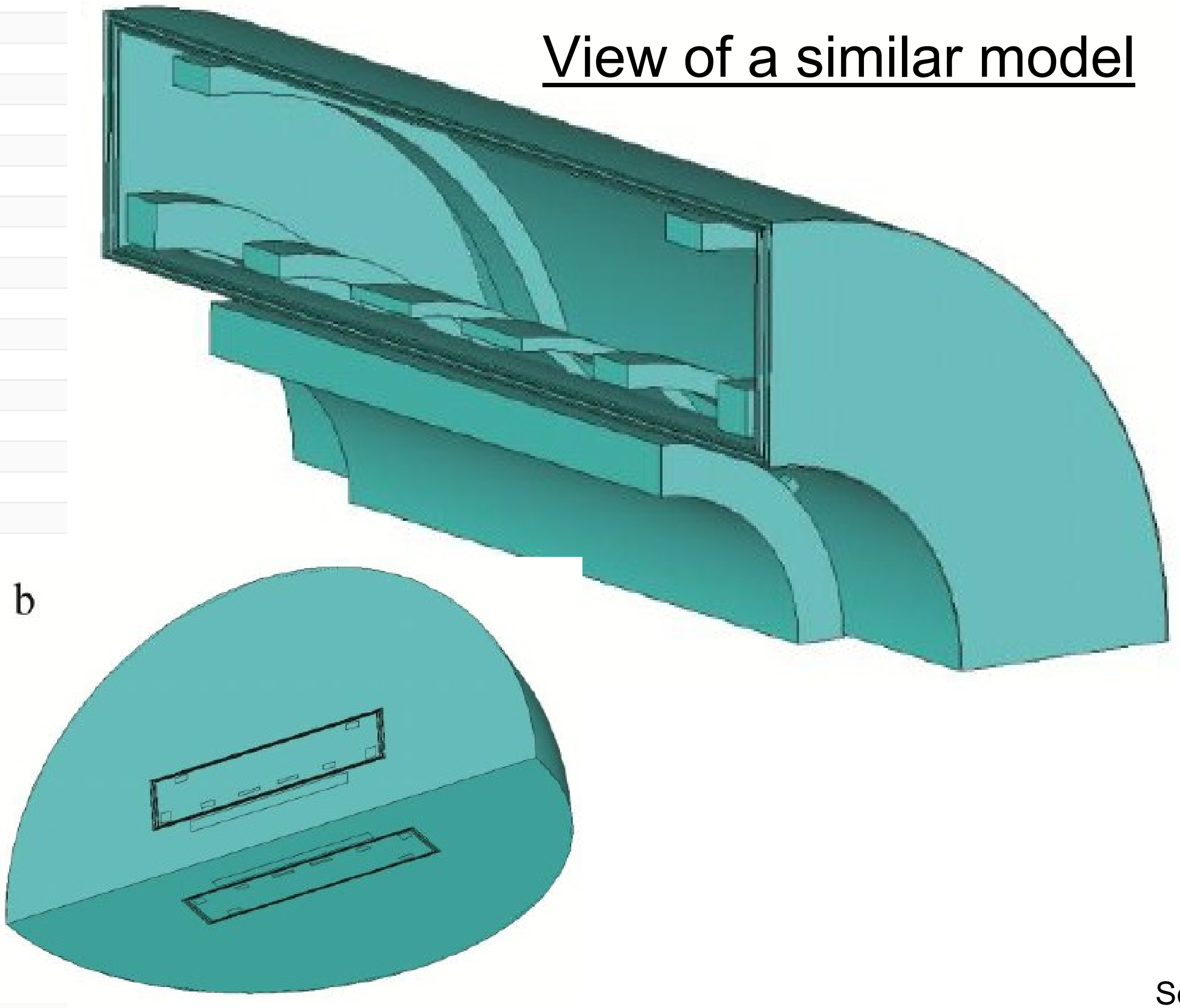


Image source [Wang]

14. Acoustics model (simplified representation)

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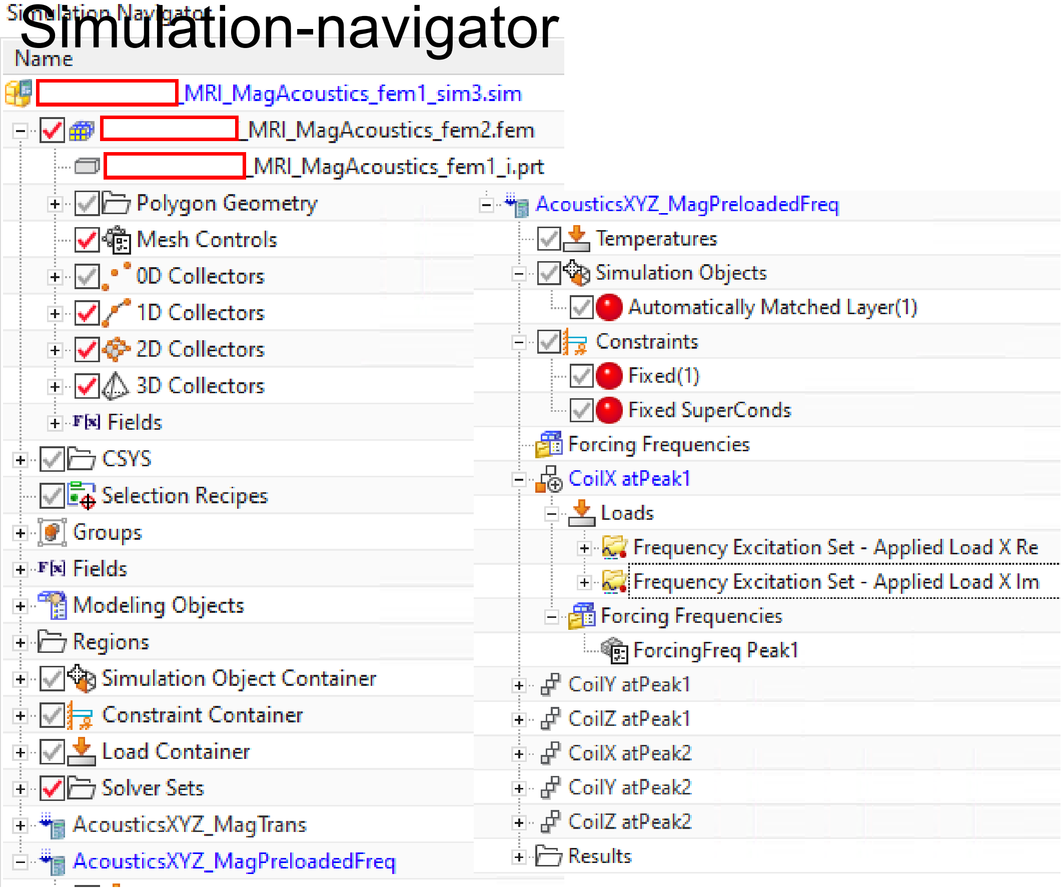
Numbers

- Elements: 5.647.392 nodes: 989.352 mass elements: 2.848
- Beam-Elements: 158.362 spring-Elements: 74

Simulation-navigator



View of a similar model

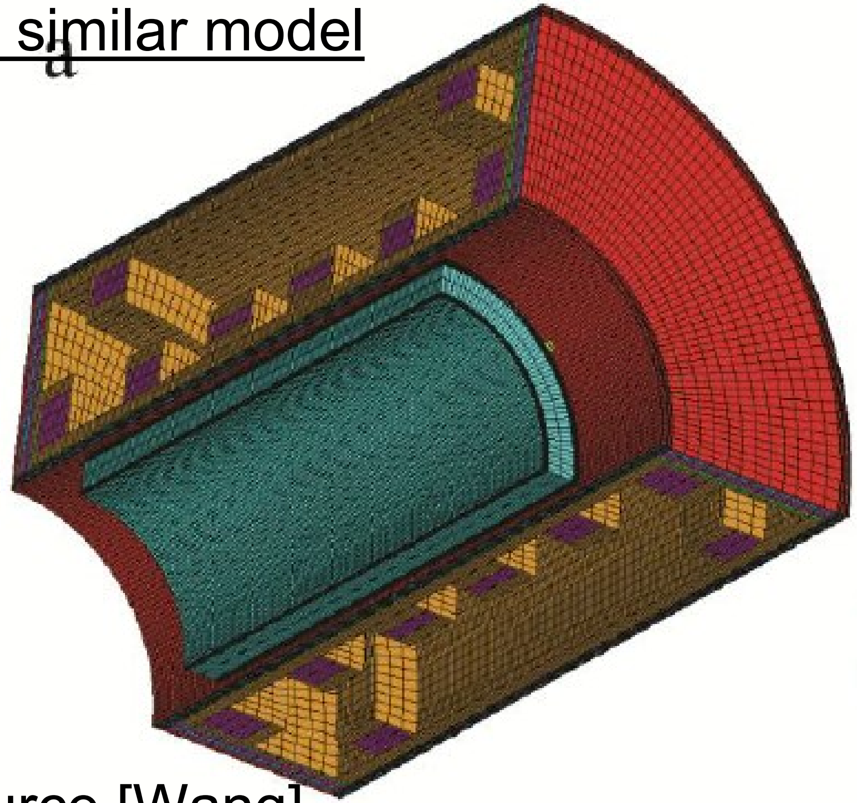


Image source [Wang]

15. Typical acoustics result

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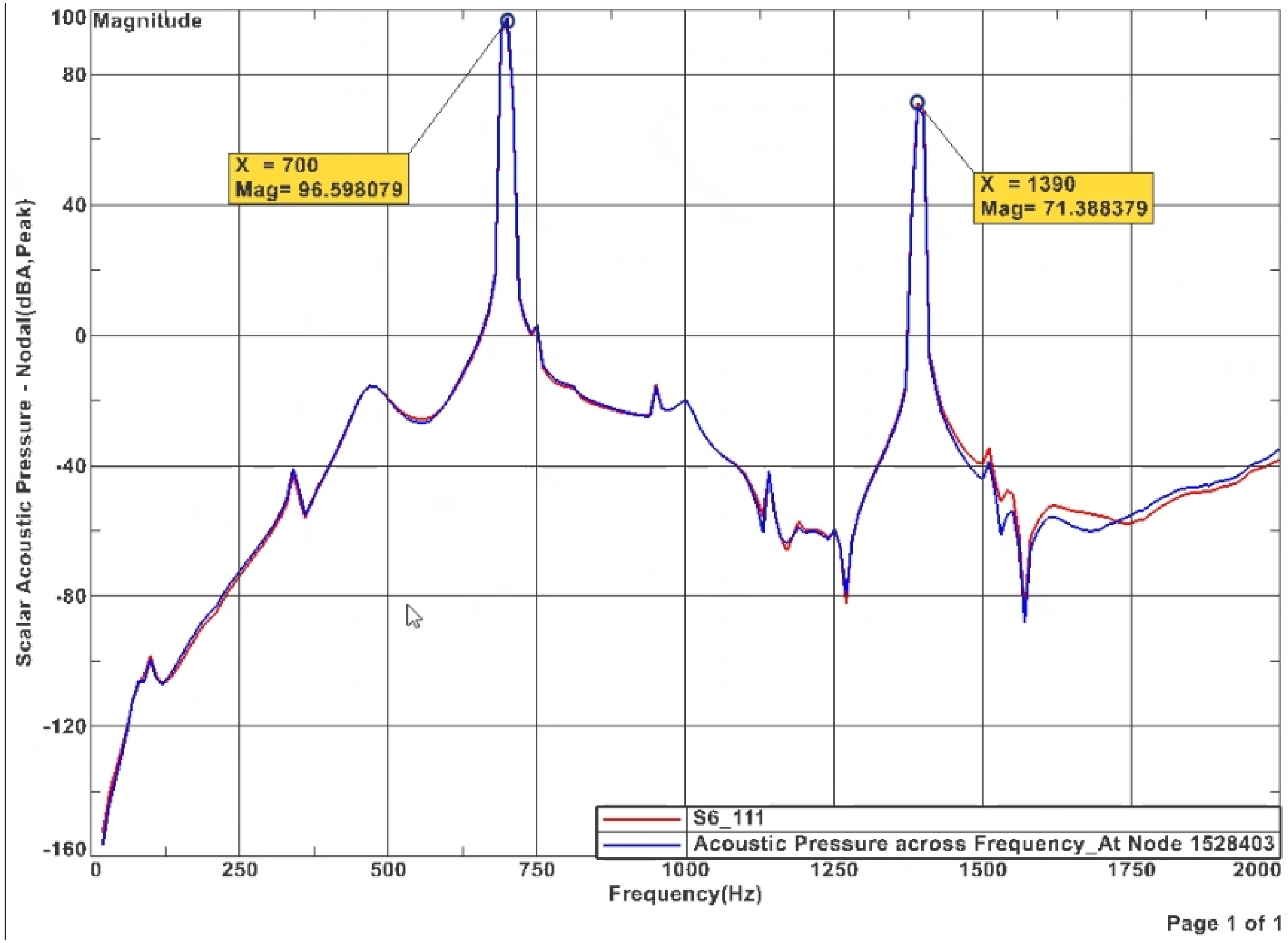
The illustration shows a typical acoustic result as it can occur at a result position.



16. Result plots of the sound pressure

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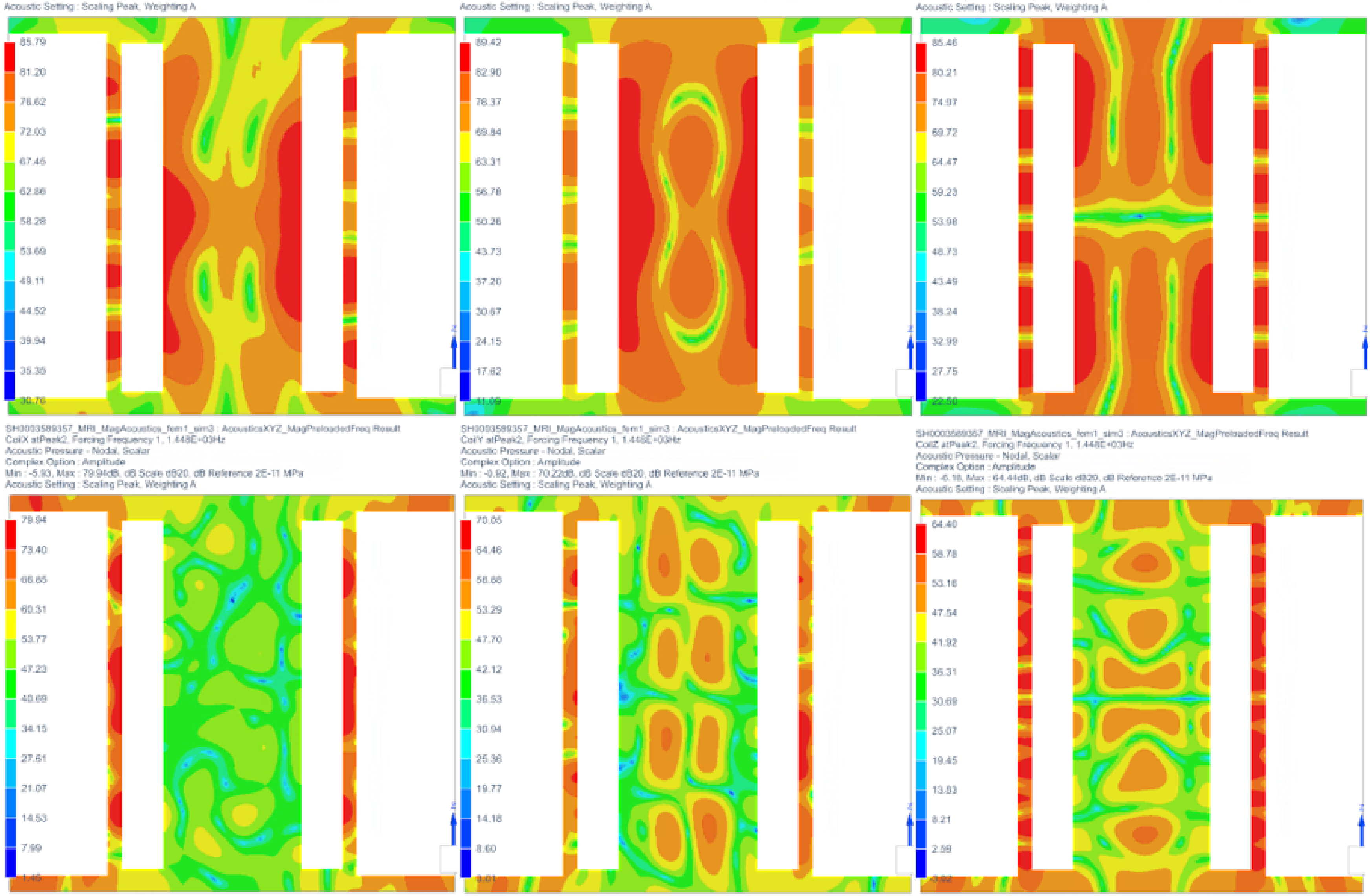
Acoustic sound pressure in dB(A), top (from left to right): Coil x,y,z Peak1 , bottom: peak 2



17. Adaptation to the measurements

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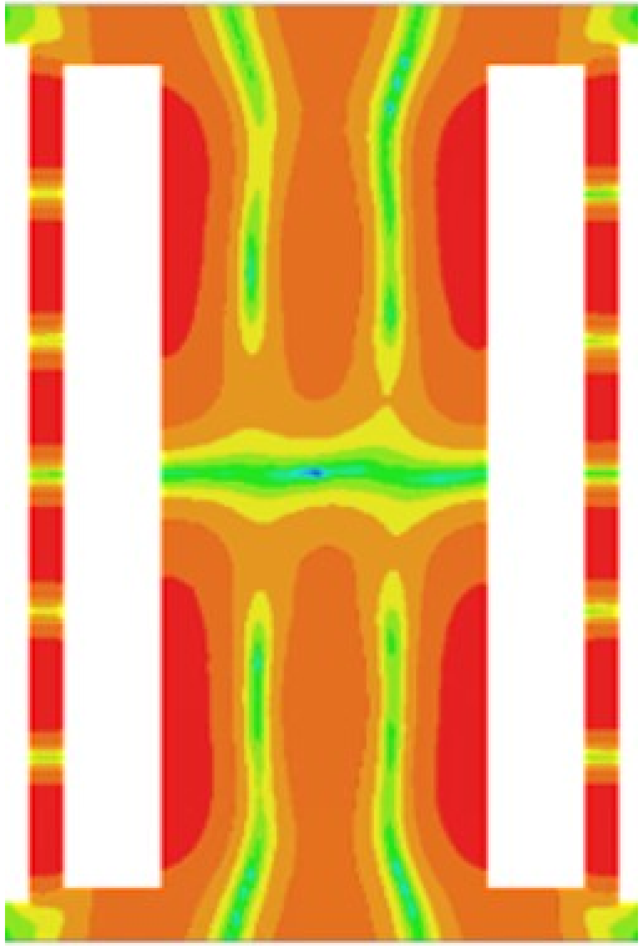
Approximately 100 simulations were carried out with the aim of adapting the simulation model to the 30 acoustic measurement results. Here are some examples of variations:

- Reducing/increasing the acoustic frequency sampling rate
- Adding/removing mass
- Changing the modulus of elasticity of the coil windings and the resin
- Changing the spring stiffness of the connections from gradient coils to the housing or from housing to ground
- Without housing or with housing
- Reading points close to the actual measuring point
- Changing the parameters of the Fourier transformation
- Changing the FEM element orders: Center node on/off, as well as the element size
- Magnetics: with/without impedance boundary condition on the housing
- Nastran: Modal reduction (Sol111) or direct solution (Sol108)
- More or less damping for acoustic simulation



18. Literature, sources

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[Wang]
PhD Thesis of Yaohui Wang, University of Queensland in 2017

[Zeitler]
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