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PARAMETRIC MODEL OF AN AIR-CORE MEASURING TRANSFORMER

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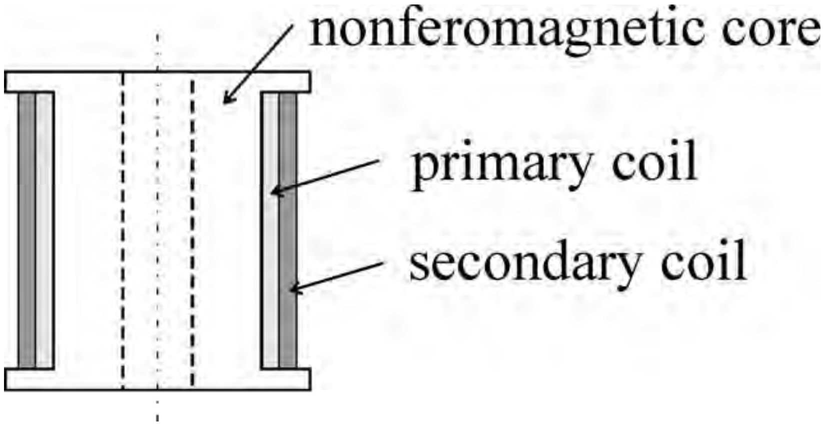
Introduction

- determining power quality in power distribution systems
- harmonic distortion in the voltage and current waveforms
- measurements of such voltage with harmonics
- new developed instrument
- the input unit:

  small air-core transformer base probe



Air-core transformer base probe

- Non-sinusoidal measured voltage on primary coil:

$$u_1(t) = \sum_{i=1}^{n} \left(U_{1m}\right)_i \cos(2\pi f_i \cdot t)$$

n - number of harmonics; f - frequency (50-2.5kHz)

- Induced voltage on secondary coil:

$$EMF(t) = u_2(t) = \sum_{i=1}^{n} \left(U_{2m}\right)_i \cos(2\pi f_i \cdot t)$$

- Transformer ratio should be constant for all freq.

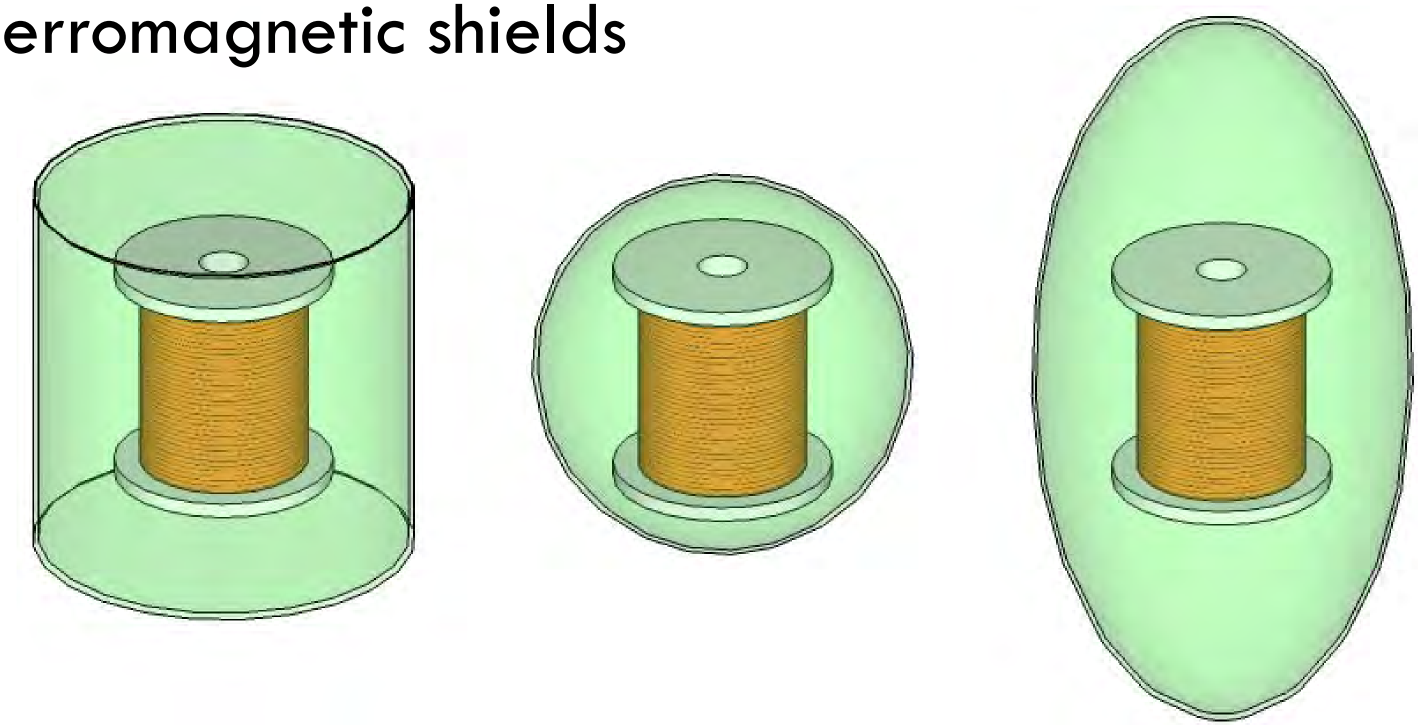
$$\left(\frac{U_{2m}}{U_{1m}}\right)_i = const.$$

External EM fields and shielding

- The goal of this work is to design a feromagnetic shield around the probe in order to protect it from the impact of external magnetic field.
  - **Optimize the shield shape** to cancel the impact of external magnetic field as much as possible (shielding effectiveness was investigated)
  - **Minimize the influence** of the shield shape on the transformer probe reading (transformer linearity coefficient was investigated)

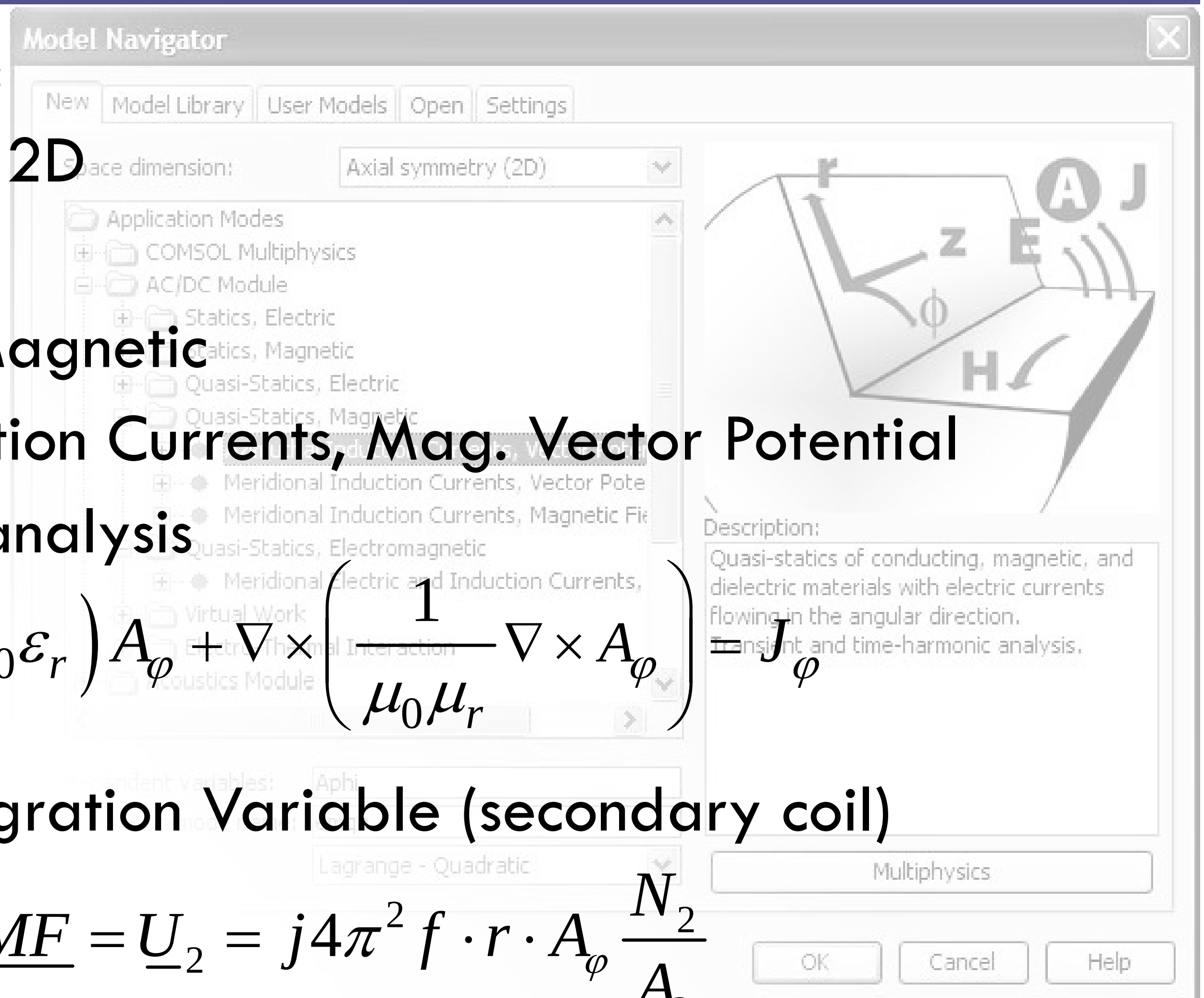
Shield shapes

- The probe was centered inside different types of ferromagnetic shields



- Shape, size, thickness, material properties (σ, μ)

Modeling - COMSOL Multiphysics 3.5a



Application Mode:

- Axial symmetry 2D
- AC/DC Module
- Quasi-Statics, Magnetic
- Azimuthal Induction Currents, Mag. Vector Potential
- Time-harmonic analysis

$$\left(j\omega\sigma-\omega^{2}\varepsilon_{0}\varepsilon_{r}\right)A_{\varphi}+\nabla\times\left(\frac{1}{\mu_{0}\mu_{r}}\nabla\times A_{\varphi}\right)=J_{\varphi}$$

- Subdomain Integration Variable (secondary coil)

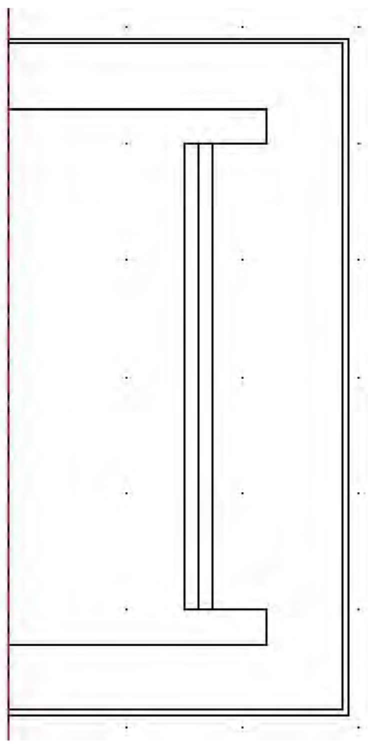
$$\underline{EMF}=\underline{U}_{2}=j4\pi^{2}f\cdot r\cdot A_{\varphi}\frac{N_{2}}{A_{2}}$$

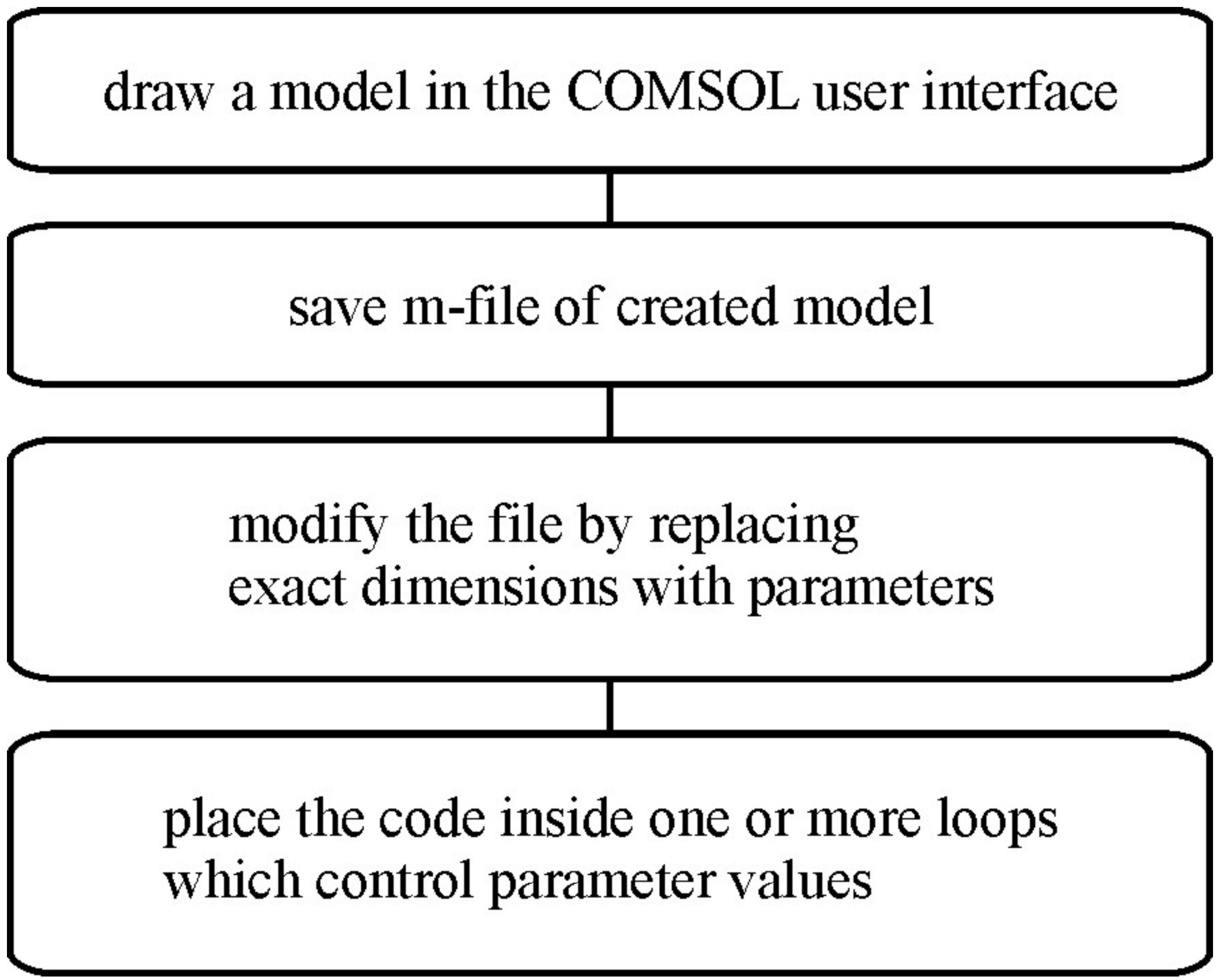
Parametric model approach

- Several ways to create a parametric model can be employed
  - geometric parametric sweeps option in COMSOL Multiphysics v3.5a, in connections with a specialized CAD software, such as SolidWorks and AutoDesk Inventor,
  - moving mesh (ALE model)
  - programming in MATLAB.
- The last approach was chosen as it allows varying geometric dimensions without changing the model topology in numerical simulations.

Connection with MATLAB

- Creating parametric model





Geometry modeling

- Using COMSOL GUI or MATLAB
- Basic geometry objects: rect2, circ2, curve2… geometry functions: geomcomp, geomcsg, …

- Analyze and update the geometry data by using geomanalyze (e.g. moving objects)

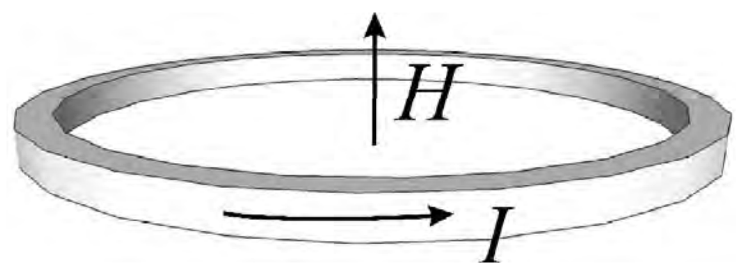
  If the indexing of subdomains stays constant while the values of geometry parameters are changing, then geomanalyze is not needed.

Creating the mesh

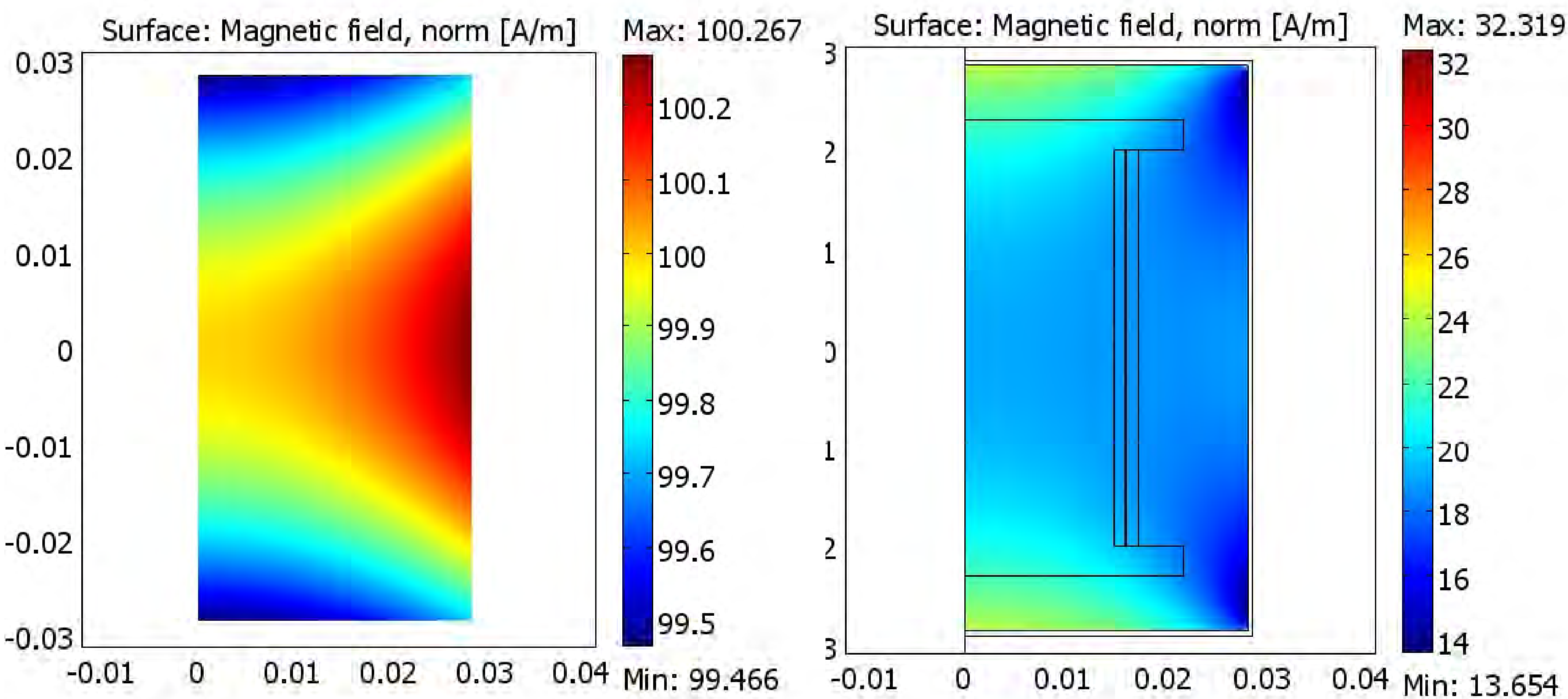
- The number of mesh elements will be changed inside the loop, depending on the skin depth and the thickness of shield.
- Element size of the shield subdomain is related to the skin depth of the ferromagnetic material of shield
- The skin depth is about 7 times smaller for the 50^{th} harmonic than for the fundamental frequency at 50Hz.

External magnetic field in simulations

- Standard CEI EN 61000-4-8:
  - circular or square coil
  - testing area can be up to 60% the of the coil diameter
  - up to 3dB inhomogenity of magnetic field
- In simulations:
  - magnetic field strength 100A/m (5. level)
  - Diameter 1m
  - Inside the testing area (less than 10% of the diameter), the amplitude of time harmonic magnetic field is changed not more than 5%.



When the external magnetic field (50Hz) is present, the magnetic field inside the shielded probe is approx. 20A/m (5 times less than without the shield)

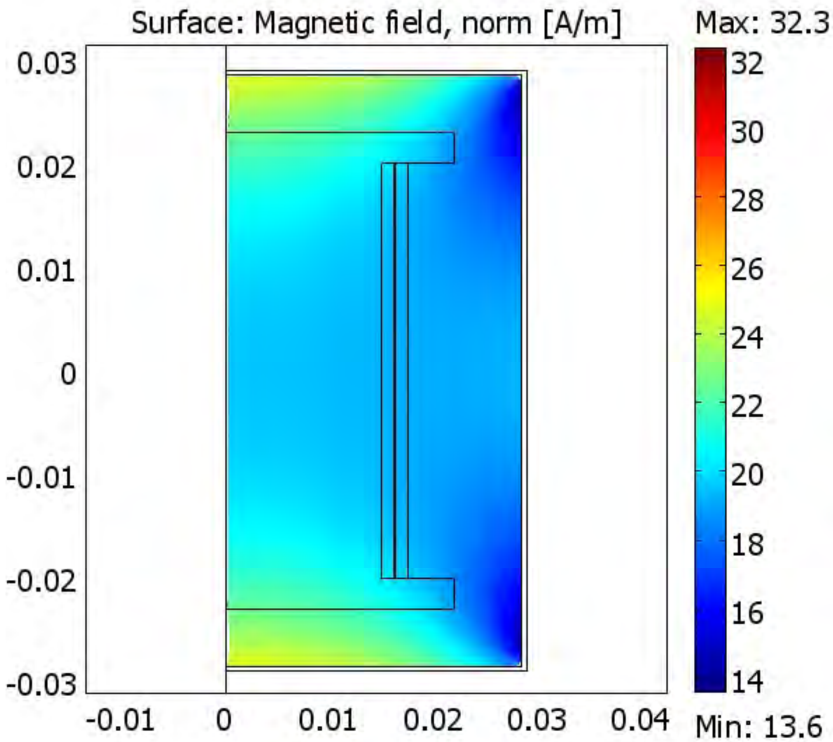


without shield

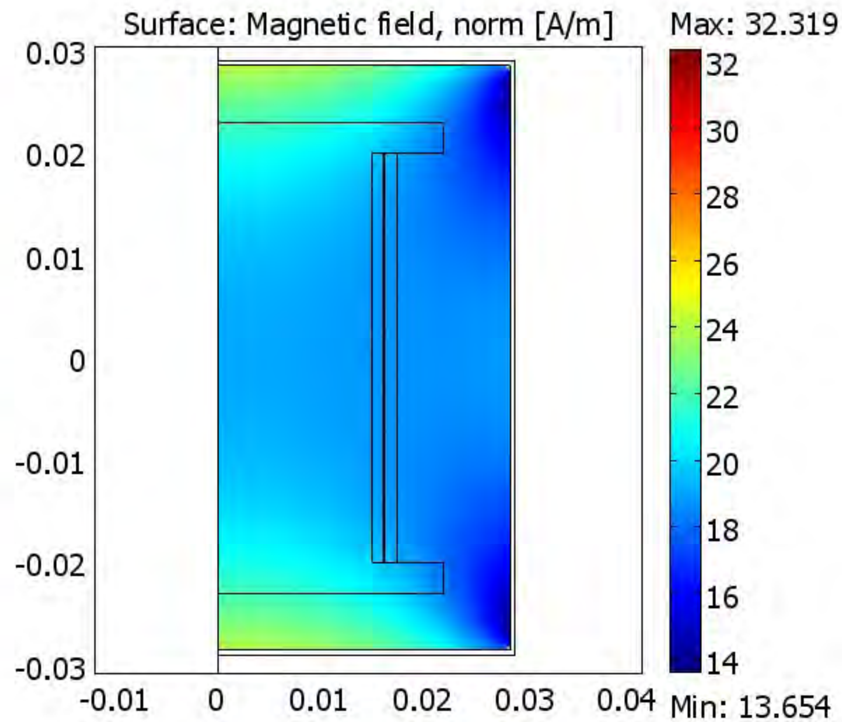
with shield
(R=28.5mm, H=2R, d=0.5mm)

Reduced potential

- Magnetic vector potential $A = \left(A_{\varphi\_\mathrm{red}} + A_{\varphi\_\mathrm{ext}} \right) \boldsymbol{e}_{\varphi}$



Reduced potential



Circular coil

The shielding effectiveness and the transformer linearity coefficient

- The shielding effectiveness is defined as a ratio of the two magnetic flux densities, without and with the shield present.

$$S_e = \frac{B_0}{B_{sh}} = \frac{EMF_0}{EMF}$$

- The transformer linearity coefficient was defined as

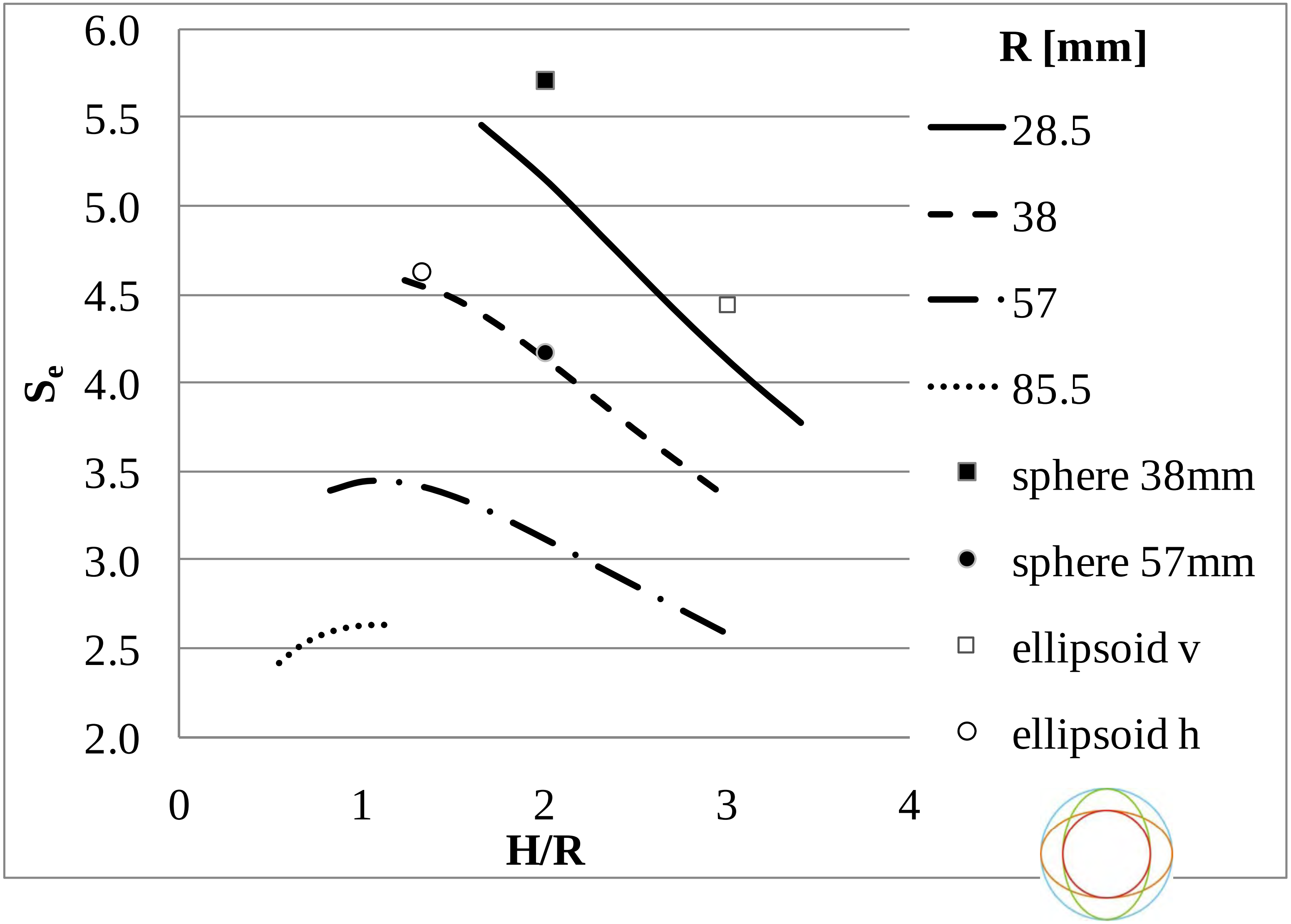
$$k = \frac{EMF}{freq}$$

(unshielded case 0.1553 mV/Hz)

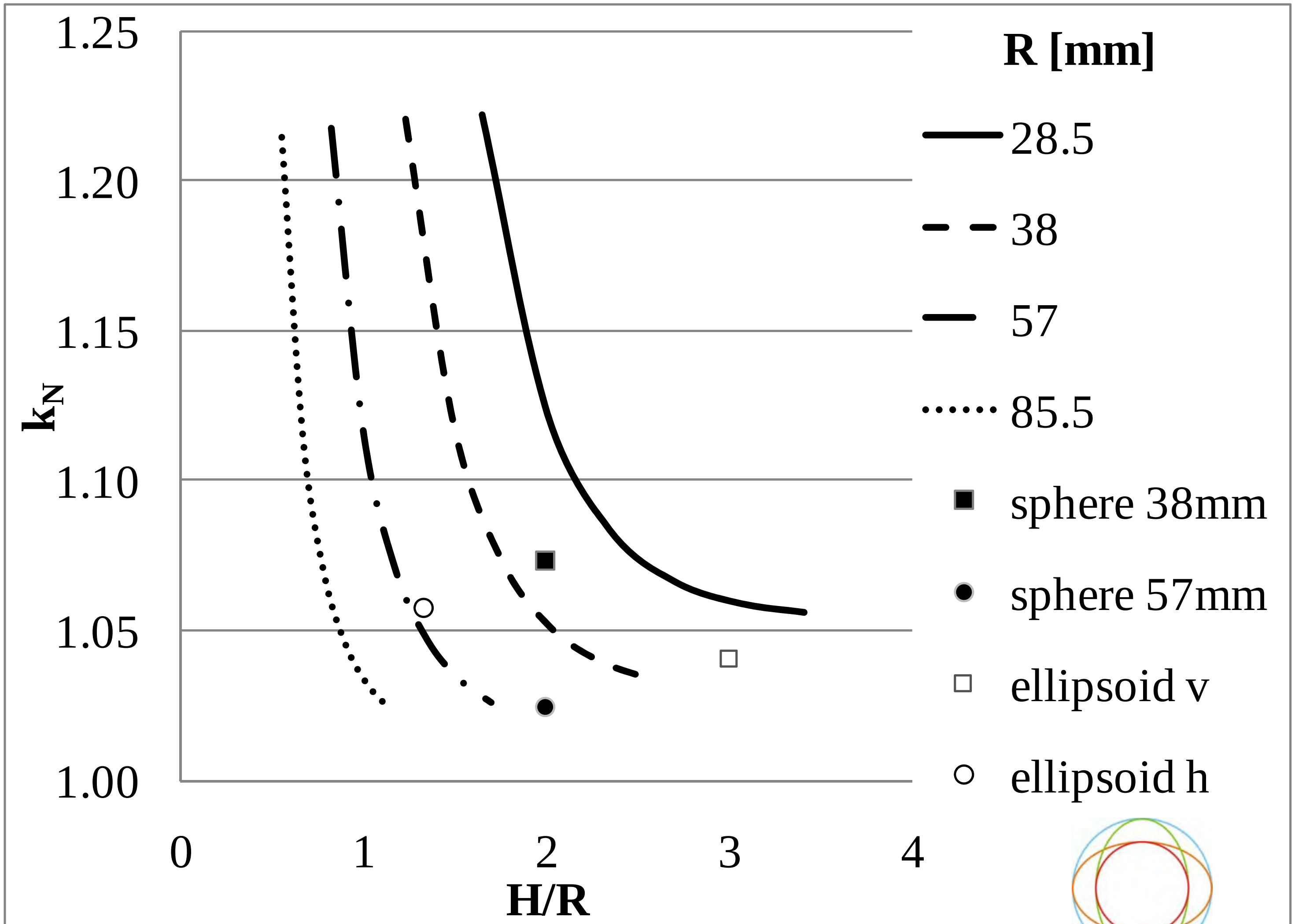
- The normalized transformer linearity coefficient is

$$k_N = \frac{EMF}{EMF_0} = \frac{L}{L_0}$$

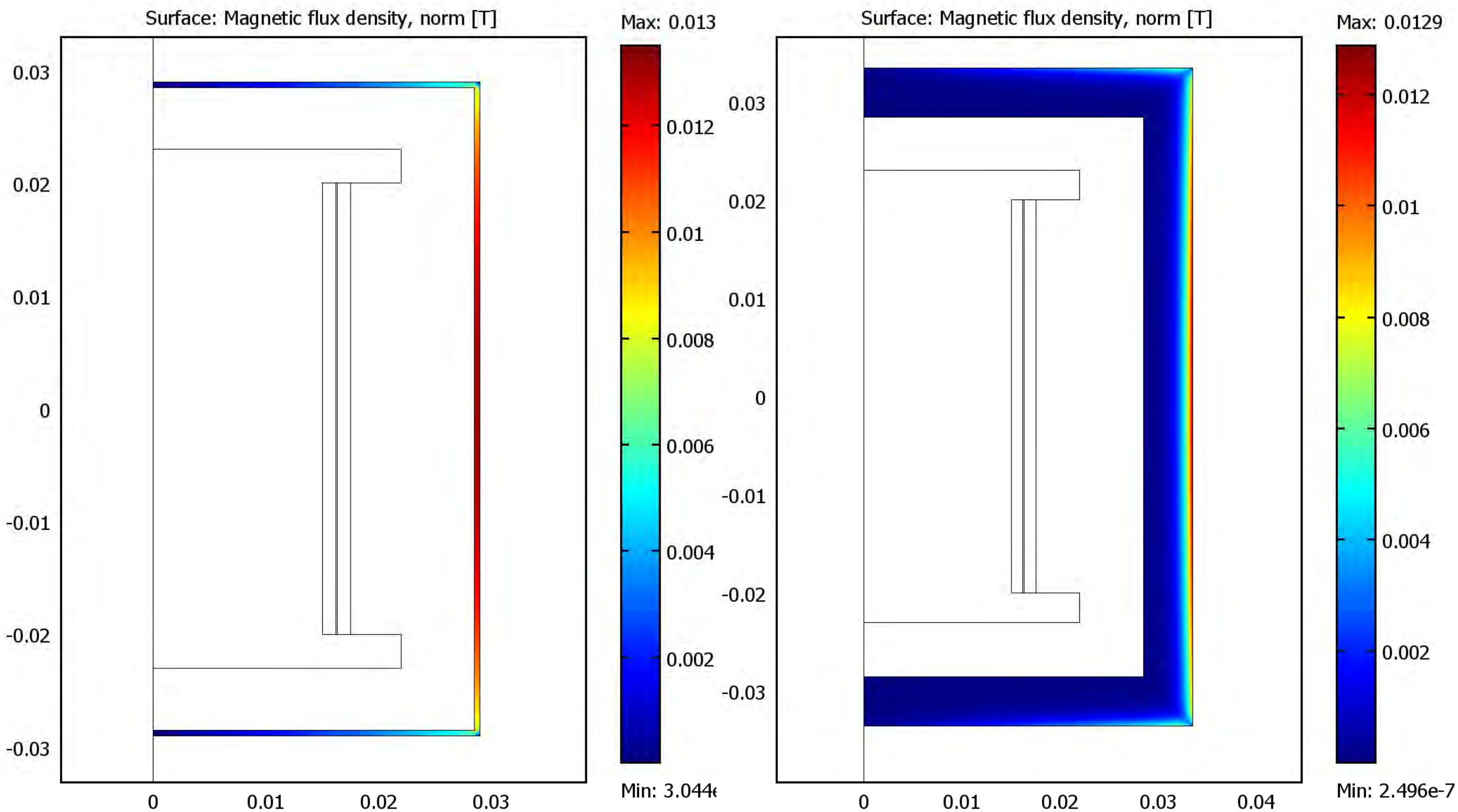
Shielding efficiency as a function of H/R ratio for different shield shapes (thickness of shield 0.5mm)



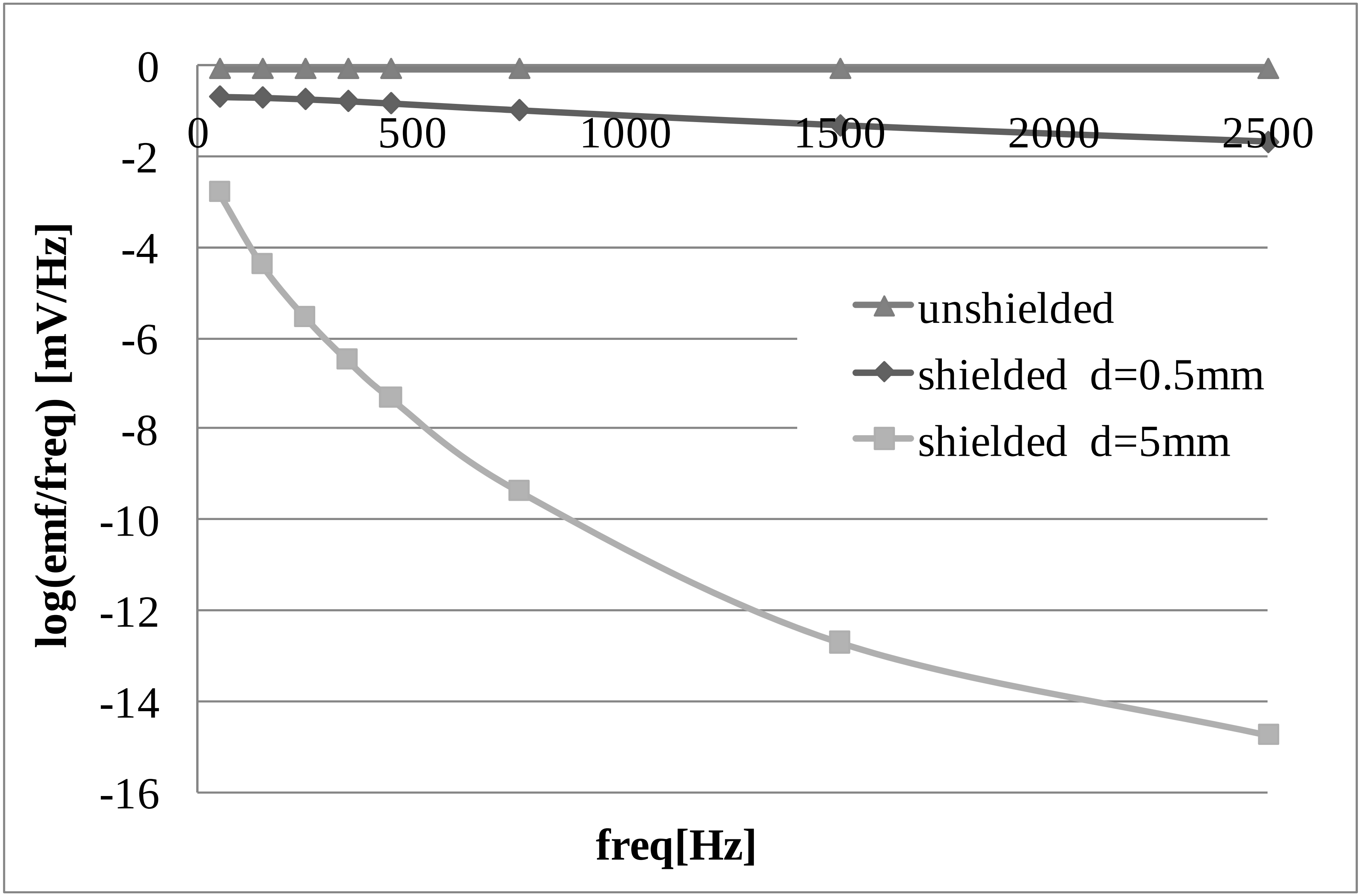
Normalized coefficient k_N in function of H/R ratio for different shield shapes (same thickness 0.5mm and μr 550 for all shields)



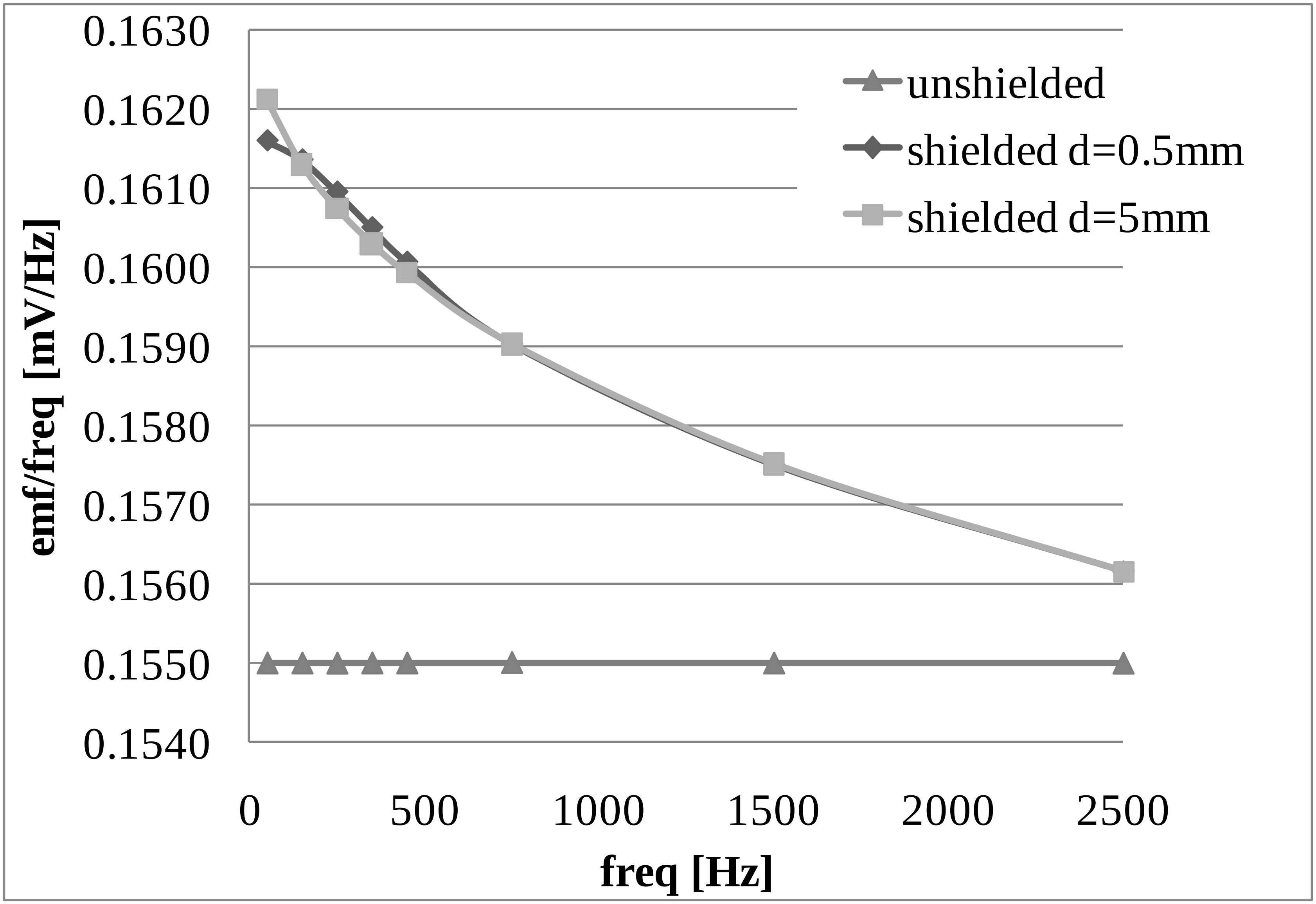
Distribution of magnetic flux density along the shield due to external time harmonic magnetic field at 50Hz
(thickness of the shields 0.5mm and 5mm)



Impact of external magnetic field is expressed by the transformer linearity coefficient as a function of magnetic field frequency



Shield shape influence on transformer linearity coefficient as function of frequency of input signal on primary winding



Conclusion

- COMSOL Multiphysics is a very useful FEM based tool for a wide range of applications.
- The parameterized probe model was created and used for a large number of simulations in order to find appropriate solution of this particular task.
- Parametrizing the models can be complicated.
- From the discussed range of the shields, the spherical shields performed best, as expected from theory.

Conclusion

- However, without COMSOL it would be impossible to conclude what shield shapes and sizes are most appropriate.
- A cylinder of particular dimensions can be a sufficiently good solution.
- Future work will employ an optimization technique together with an appropriate fitness function introduced into COMSOL and used for the optimum search.

Acknowledgement

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