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COIL DESIGN WITH LITZE WIRE FOR MAGNETIC PARTICLE SPECTROMETRY

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Abstract. *The design of an excitation coil for magnetic particles spectrometer (MPS) was described. It was assumed that the spectrometer should measure the spectra of particles of diameter in the range 10-100 nm. To measure the amplitude and phase angle spectra of magnetic nanoparticles it is required to generate sinusoidal alternating spatially homogeneous magnetic field of magnitude of 20 mT. The work volume of the designed spectrometer was 20×20×20 mm allowing measurement of small samples. The estimation of magnetic properties of magnetic nanoparticles is crucial in Magnetic Particles Imaging. In this paper we described the excitation coil design which minimizes power losses on the coil related to heat emission. The resonance circuit operating on 20 kHz frequency was applied. Optimal litze wire configuration was proposed to negate skin and proximity effects. The numeric simulations for the optimal and commercially available suboptimal litze wire configurations were performed. The comparison of the results was shown and discussed.*

Keywords: magnetic field, nanoparticles, coils, spectroscopy

KONSTRUKCJA CEWKI Z WYKORZYSTANIEM LICA DO SPEKTROMETRII CZĄSTEK MAGNETYCZNYCH

Abstrakt. W artykule tym została opisana konstrukcja cewki pobudzającej do wykorzystania w spektroskopii cząstek magnetycznych. W projekcie złożono, że spektrometr, którego częścią będzie cewka, będzie w stanie mierzyć widma odpowiedzi nanocząsteczek o średnicy od 10 d0 100 nm. Do skutecznego pomiaru widm amplitudowych i fazowych cząstek magnetycznych potrzebne jest pobudzenie ich sinusoidalnie zmiennym w czasie, ale przestrzenie jednorodnym polem magnetycznym o amplitudzie powyżej 20 mT przy częstotliwości 20 kHz. Robocza objętość projektowanego spektrometru została ustalona na 20×20×20 mm, co pozwala na pomiar małych próbek. Estymacja parametrów magnetycznych nanocząsteczek jest niezwykle ważna do prawidłowego odtworzenia obrazu w tomografii nanocząsteczek magnetycznych. Opisana w artykule konstrukcja cewki pobudzającej pozwala na minimalizacje strat mocy na cewce i związanego z tym przegrzewania się układu. Zaproponowana optymalna konfiguracja lica pozwala skutecznie zmniejszyć wpływ efektu naskórkowego i efektu zbliżenia. Zastosowano również układ rezonansowy pracujący przy częstotliwości 20 kHz. Przeprowadzono symulacje numeryczne pola generowanego przez cewki z wykorzystaniem zarówno optymalnych rozwiązań, jak i dostępnych na rynku konfiguracji drutu lica. W artykule zaprezentowano oraz omówiono wyniki części tych symulacji.

Słowa kluczowe: pole magnetyczne, nanocząstki, cewki, spektroskopia

Introduction

Magnetic Particles Spectrometry (MPS) is a measurement technique can be used to directly acquire amplitude and phase spectra of magnetic nanoparticles magnetization signal [1]. Knowledge of amplitude spectrum allows to estimate the distribution of particle size, while phase angle can allow research the impact of various parameters on nanoparticle's Brownian motion. By combining information from both of those sources valuable information about the particle's environment can be gathered. Such information are essential for the Magnetic Particles Imaging (MPI). It is a tomographic technique that allows to visualize the spatial distribution of superparamagnetic nanoparticles in a living body. Quality and value of those measurement is highly dependent on the type and parameters of the nanoparticles used as well as the properties of the environment that they are in.

The motivation for this work was to design a excitation coil able to generate sinusoidal alternating magnetic field of magnitude of at least 20 mT, which is necessary to correctly excite nanoparticles in Magnetic Particles Spectroscopy. Due to signal acquisition method used this field should be highly homogeneous in a volume of at least 50 cm^3. Coil should also be suitable to work in resonance circuit set to excitation frequency, in this case 20 kHz. The main challenges that had to be overcome were skin effect and proximity effect. Ideal solution was to use the litze wire as winding of the coil.

1. Theory

Magnetic Particles Spectrometry (MPS) measures spectra of superparamagnetic nanoparticles, typically iron oxide nanoparticles.

Superparamagnetism is form of magnetism that shares some characteristics with both ferromagnetism and paramagnetism. It occurs in typically ferromagnetic materials in very specific conditions. Nanoparticles of such material have to be separated from each other magnetically and/or spatially to be considered independent magnetic domains. Such circumstances are present for example in iron-oxide particles of diameter between 10 to 100 nm, coated with thick enough layer of polymer. Ideal superparamagnets have nonlinear magnetization curve (Fig. 1), undergo saturation in high external magnetic field after which they magnetize linearly like paramagnets and do not magnetize permanently.

Magnetization M of superparamagnets can be described by Langevin's theory of paramagnetism:

$$M(t) = m_s c_p (\coth(kH_D(t)) - \frac{1}{kH_D(t)}) \tag{1}$$

where c_p – particles concentration, H_D – magnetic field strength, $k=(\mu_0 m_s)/(k_B T)$, μ_0 – magnetic permeability of vacuum, k_B – Boltzman's constant, T – temperature, m_s – magnetic momentum of saturation, equal to: $m_s=1/6\ \pi d_c^3 M_s$, where M_s is saturation magnetization of magnetite and d_c is diameter of nanoparticle.

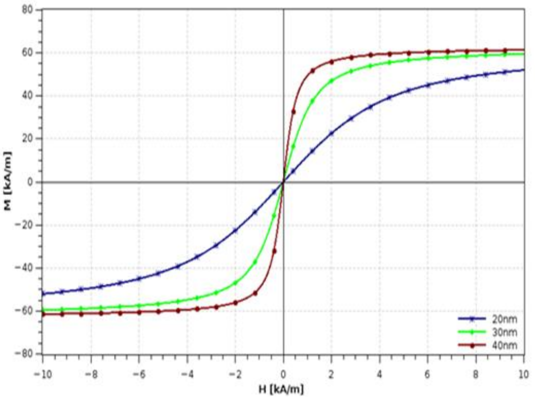

Fig. 1. Magnetization curves of nanoparticles of different diameter calculated using Langevin's equation

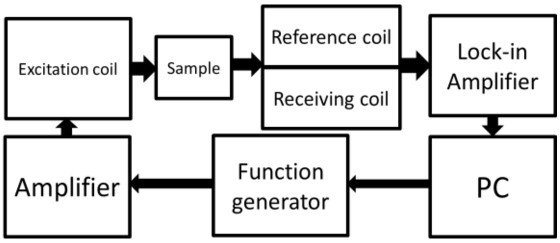

Fig. 2. Possible MPS measurement setup using Lock-in amplifier and pait of reference/receiving coils

In MPS nanoparticles are excited by sinusoidal magnetic signal generated by excitation coil. Magnetization signal from nanoparticles and excitation signal is than pick up by receiving coil. Of course excitation signal is much higher than magnetization signal of nanoparticles. Fortunately, due to nonlinear magnetization curve, signal from particles consists of harmonics of excitation frequency. Those harmonics can be distinguished from excitation signal and measured. One possible setup involves the use of matched pair of reference and receiving coils (Fig. 2). First one picks up only excitation signal, while second one both excitation and magnetization signals. By connecting them in opposite direction or applying those signal to differential input of lock-in amplifier most of excitation signal can be dampened. In MPS both amplitude and phase angle of those harmonics are measured [2]. Spectrum in MPS is defined as amplitude or phase of magnetization signal in function of harmonics of excitation frequency.

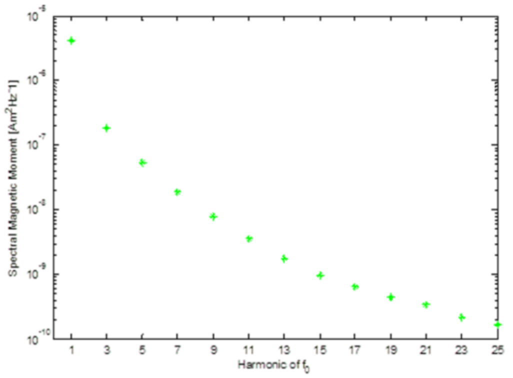

Fig. 3. Example of amplitude spectrum of nanoparticles magnetization signal measured in MPS. In MPS amplitude of each harmonic is typically given as spectral magnetic moment.

To acquire full signal of harmonics nanoparticles have to be excite with magnetic field strong enough to work on nonlinear part of magnetization curve. For most of nanoparticles such field should have magnitude between 20 and 30 mT. To obtain such field appropriately high current supply have to be used and/or coil need to have high number of turn per length of coil. Both of this conditions increase the power dissipated at the coil, which have to be limited not to overheat the coil. Thus restricting the maximal magnitude of magnetic field that can be produces by specific coil.

Frequency of excitation fields used in MPS range from 10 kHz up to 150 kHz. In this frequency range result of skin and proximity effects start to be quite noticeable. Skin effect manifests in the tendency of an AC current to become distributed unevenly within a conductor such that the current density is largest near the surface of the conductor. It is caused by opposing eddy currents induced in the changing magnetic field resulting from the alternating current flowing through the conductor. Due to skin effect the effective resistance of the conductor increases at higher frequencies. In frequency range typical to MPS skin depth (δ) through which current is flowing can be calculated as:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_0\mu_r}} \tag{2}$$

where ρ is resistivity of the conductor, ω is angular frequency of current, μ_0 is the permeability of free space and μ_r is relative magnetic permeability of the conductor. One of possible solution to overcome this effect is use of so called litz wire [3].

Litz wire is a multi-strand cable in which electrically isolated single wires are braided in specific patterns, often consisting of several levels (bundles of signal wires stranded together). Diameter of single wire is much smaller than skin depth for working frequency, thus there is no skin effect on the wire-level. But use of multiple wires causes another detrimental effect to occur called proximity effect.

Proximity effect is also caused by opposing eddy currents but in this case induced by magnetic fields from currents in separate wires. It also contributes to increase of power losses, but by twisting the wires, with the pitch of twisting much small than the overall length of wire, proximity effect can be highly mitigated.

To prevent skin effect on the bundle-level Litz wire has to be constructed with multiple levels of twisting. Firstly cross section area of a bundle needs to be smaller or equal to cross section area of wire of maximum diameter in which there is no skin effect. In this case the approximate maximum recommended number of single wires to be twisted together in the bundle is:

$$n_{\max} = 4\frac{\delta^2}{d_s^2} \tag{3}$$

where δ is the skin depth for a solid conductor given by (2) and d_s is the diameter of an individual wire. Secondly while twisted bundles need to be transposed between different radial positions over the length Litz wire. Possible approach to make sure that skin effect is avoided between the bundles is to twist no more than five bundles together. A group of five or fewer has no bundle in the center, so radial position of each bundle changes over the length of the cable. Whereas a group of seven has six around the outside and one in the center, which one would not change its radial position. That is why in some cases it is preferred to use multi-level constructions, each time using 5 or less sub-bundles.

2. Material and Methods

In design of our previous excitation coil [4], which was of Helmholtz type, we used single wire of diameter below skin depth (which in case of 10 kHz is about 0.6 mm) to ensure that skin effect was not present. Resonance circuit set to excitation frequency was used so that most of impedance due to reactance could be neglected. This resulted in magnetic field of magnitude of less than 8 mT even when power dissipated on coil was over 400 W and current of 6 A. Unfortunately due high power losses both coil and resonance circuit heated up and resonance frequency fluctuated resulting in impedance of the coil higher than anticipated. Higher impedance may also been caused by proximity effect which was not considered than. Such amplitude was not enough to fully saturate magnetic particles that we used as sample. Furthermore use of reference coil was impeded by both inhomogeneity of generated field and construction of exaction coil.

Contrary to our previous work this excitation coil will be a solenoid. It will be bigger than most MPS excitation coils, with inner diameter of 30 mm and length of 200 mm, because we are planning to use it also as excitation coil for Magnetic Particles Imaging Scanner in the future. Bigger volume of homogenous field should also allow improve use of reference coils, as both receiving and reference coils can be stimulated be same field.

To mitigate both skin and proximity effect in this design we decided to apply litz wire. Litz wire that we considered the best option after theoretical analysis was in configuration of 5×21×0.2 mm (which means 5 bundles of 21 single wires of diameter of 0.2 mm). Such litze wire should work best for frequencies between 10 to 20 kHz. According to our rough theoretical calculations it should be able to generate magnetic field with amplitude of 30 mT, while powers dissipated on it will be of about 120 W. To make sure that our calculations were correct we performed numerical simulations of magnetic field (Fig. 2, 3, 4).

The simulations were conducted in Comsol. We assumed that we will be able to wind at least 3 layers of Litz wire. Filling factor of coil was set to 80%. Current flowing through coil was set so that power losses would be less than 120 W.

Unfortunately not only such ideal configuration was not available on the market but also manufacture and purchase of not mass produced litze wire is quite expensive. Due to this reasons it was decided to buy cheaper but suboptimal wire. This configuration of wire was chosen by applying same theoretical principles as in optimal case but taking into account only configuration that was available on the market. From those litze wire in configuration of 7×90×0.1 mm was selected. The simulation fallowing the same assumptions as one for optimal configuration was performed for coil made of this suboptimal wire (Fig. 5, 6).

Design of bobbin for the coil is shown in the Fig. 1. As coil will be water cooled slots along the surface of bobbin are to ensure the flow of water also under the wires. By encasing the coil in an rubber tube it should be possible to efficiently force the flow of water if necessary.

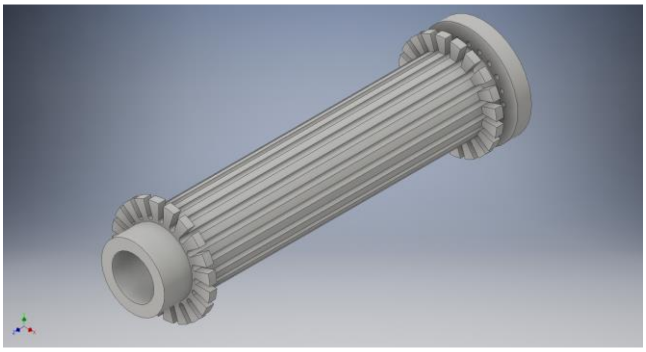

Fig. 4. 3D model of the coil's bobbin

Fig. 5. Manufactured Litz wire excitation coil

Manufactured coil's bobbin is made of PTFE (Teflon) to allow work to up to 200 °C if there is no cooling. Coil consists of about 220 turn of 7×630×0.1 mm Litz wire divided into 4 layers. To work properly coil will be connected to resonance filter set to excitation frequency.

3. Results

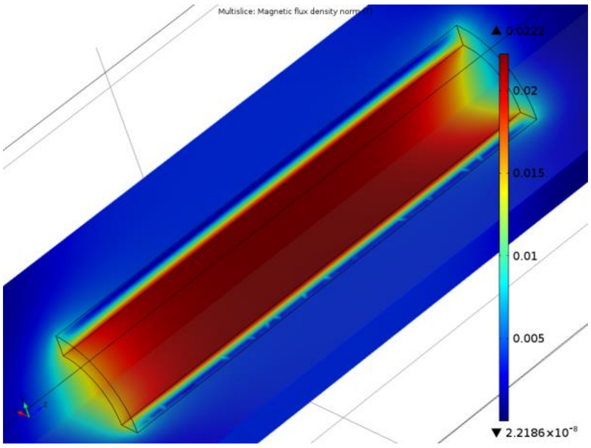

Fig. 6. 3D simulation of magnetic flux density. The value of magnetic flux density for the current value equal to 12 A

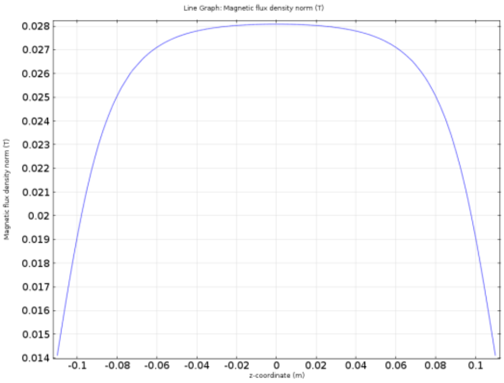

Fig. 7. The magnetic flux density along z axis. Zero corresponds to the center of the coil. Result for Litz wire in 105×0.2 mm configuration

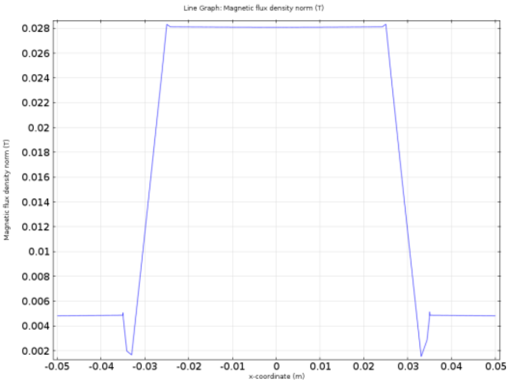

Fig. 8. The magnetic flux density along x axis. Zero corresponds to the center of the coil. Result for Litz wire in 105×0.2 mm configuration

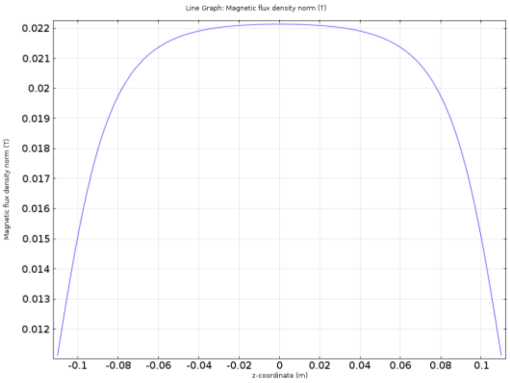

Fig. 9. The magnetic flux density along z axis. Zero corresponds to the center of the coil. Result for Litz wire in 7×90×0.1 mm configuration

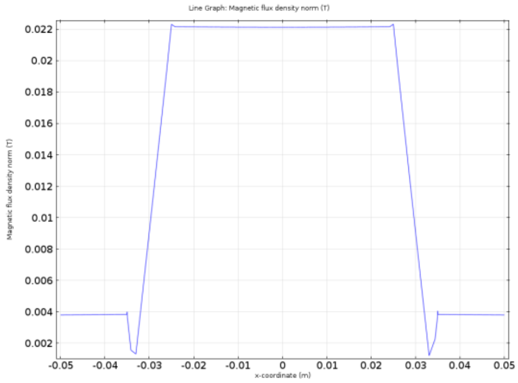

Fig. 10. The magnetic flux density along x axis. Zero corresponds to the center of the coil. Result for Litz wire in 7×90×0.1 mm configuration

4. Conclusion

According to results by use of litz wire in the resonance circuit we will be able to eliminate both skin effect and proximity effect at frequency of excitation, thus lowering the impedance of coil and improving its Q factor. It may seem that coil is too long if compared with actual working volume of spectrometer but high homogeneity of the magnetic excitation field over the length of 8 cm obtained will allow the reference and receiving coils to work efficiently. As one might expect, usage of commercially available litze wire, deviating from optimal configuration, will worsen the performance of the excitation coil but homogenous field of strength above 20 mT could still be acquired. The numerical calculations suggest that required magnetic field magnitude could be obtained with power losses of less than 120 W in the coil of proposed design. Such power losses could be compensated using simple water cooling system. Further measurements of magnetic field generate by coil are needed to confirm it. Finished coil will be used to perform actual MPS measurements.

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