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Power-optimized drive field coils for human brain magnetic particle imaging

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Abstract

The implementation of human-scale magnetic particle imaging is significantly restricted by the nonlinear growth in power with the size of the field-generating coils. To address this issue, we developed anatomically optimized shapes with a reduced internal volume for the head drive field system using a wide range of anatomical data as a reference. On the base of designed complex bodies, we synthesized windings for two orthogonal coils with the help of the stream functions approach. The resulting coil set was compared to the state-of-the-art solenoid/saddle coil pair and showed a reduction in power consumption by a factor of 1.58 in numerical simulations. We also built a prototype of the designed coils using additive manufacturing and used it to receive the first signals from the nanoparticles.

I. Introduction

The history of the development of magnetic particle imaging (MPI) as a tomographic technique started in 2005 [1]. However, so far only a few prototypes have been shown that are feasible for human use [2–5]. One of the main reasons for this is the nonlinear (at least quadratic) dependence of power on the size of the field-generating coils. This ratio imposes quite strong restrictions on hardware and leads to enormous technical complexity when the size of the field of view reaches dimensions of large body regions [2]. From this perspective, brain diagnostics appears to be one of the most promising areas where hardware optimization and proper selection of imaging tasks could help to stay at reasonable power levels. Considering the current clinical needs, a mobile head scanner for stroke detection will be in high demand. Cerebral perfusion measurements do not require high spatial resolution but can get full benefits from the imaging speed granted by MPI technology.

It has been demonstrated previously that it is possible to measure blood perfusion and detect the stroke in a simplified brain simulator using an MPI scanner with a small footprint [5]. In this work, we perform the optimization of the orthogonal set of drive field coils for an upgraded version of this system. To increase the field-to-current ratio, as well as reduce eddy currents in the conducting surfaces surrounding the coils, we used anatomical information to put coil conductors as close to the region of interest as possible.

II. Material and methods

To determine the minimum acceptable dimensions of the internal volume, we collected information from four open sources with statistical data on head sizes [6–8]. Three main parameters were considered: head width, head breadth, and head circumference (Fig. 1(a)).

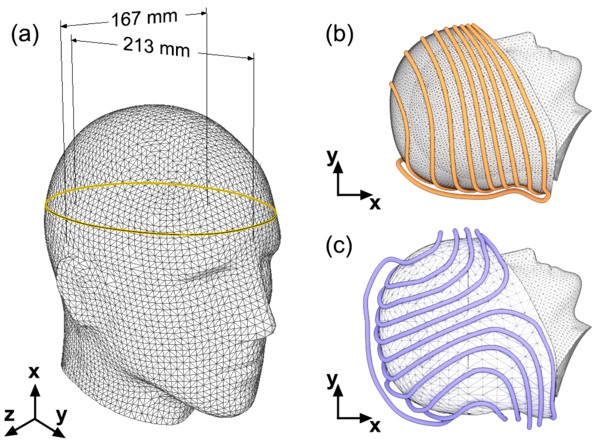

Figure 1: (a) A base head model with main dimensions. The yellow line shows the position of circumference measurements. Designed mesh surfaces are depicted together with synthesized coil windings on top of them forming first (b) and second (c) drive field coils.

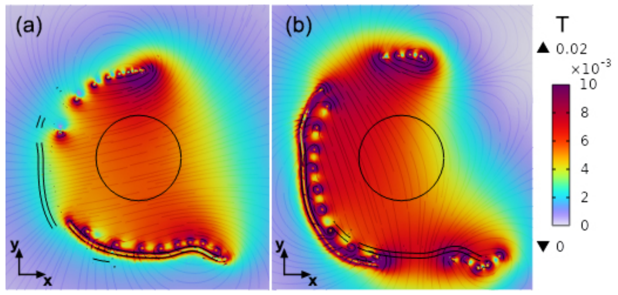

Figure 2: Numerical simulations of (a) first and (b) second layer of the synthesized coil set without shielding. The central plane (z=0) is depicted. The black circle shows the area where field uniformity was preserved by the optimization algorithm.

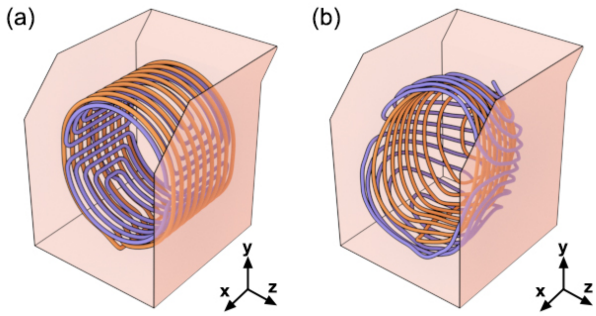

Figure 3: Models of coil pairs used in simulations. State-of-the-art solenoid/saddle coil pair (a) and power-optimized anatomically adapted coil pair (b). Both coil sets are positioned inside identical copper housings.

The resulting head model has a width of 213 mm, a breadth of 167 mm, and a circumference of 601 mm which suits the range of XL/XXL helmet sizes. Selected values of width and breadth correspond to the 99th percentile of the dimensions described in [6], larger than mean values represented in databases SizeChina and CAESAR [7] and equal to the dimensions of the 'Large_symmetry' digital head model from NIOSH Digital Headform set based on [8]. By using the generated model as a reference, we designed two surfaces that closely follow the anatomy of the head and neck. Due to the reduction of the internal volume we decided to open the face of the patient to avoid possible claustrophobic effects and make the system more accessible for clinicians. We performed coil synthesis by using the open-source software package 'bfieldtools' based on a stream function approach [9, 10]. As the main optimization criteria, we set the minimization of ohmic losses together with the constraints of 10% for a field inhomogeneity in the spherical volume with a diameter of 120 mm. The directions of the main fields for both coils were also varied. After a series of optimizations, the field direction for the first layer coil was chosen to be 20 degrees, and for the second layer coil to be 110 degrees relative to the x-axis in the xy plane. The final coil windings together with the return path wires are shown in Fig. 1(b,c). After the model was complete, we carried out numerical simulations using COMSOL (COMSOL AB, Stockholm, Sweden) software with realistic values of the currents driving both coils (162 A, 231 A, 25 kHz) to achieve a 6 mT/μ_0 average fields inside the spherical volume. The simulated magnetic flux density for both coils is depicted in Fig. 2. To compare the performance with the state-of-the-art design, we also simulated a pair of solenoid/saddle coils, with geometric parameters close to those in [5] (Fig. 3). The prototype of the coil set was built on the base of 3d printed parts and winded by using ten parallel RUPALIT V155 2000x0.05 mm (Rudolph Pack GmbH, Germany) Litz wires for each coil. During the first experiments, 176 A 25 kHz current was applied to the first layer coil to create a drive field for particle excitation.

III. Results and discussion

To test the performance in numerical simulations, we found current values for each pair of coils that would create an average field of 6 mT/μ_0 inside a sphere with a diameter of 120 mm. After that losses in coils conductors and shielding surfaces were calculated. The new coils showed a reduction in total power consumption by 1.58 times, while losses in the shields were reduced by 1.8 times. Preliminary testing of the unshielded built prototype shows good agreement between simulations and measurements for both coils producing an average field of 6/μ_0 mT: 176 A/272 A measured and 162 A/231 A simulated, respectively. To test out the capabilities of the drive field, we inserted a test sample filled with 5 ml of Synomag-D (Partikeltechnologie GmbH, Germany)

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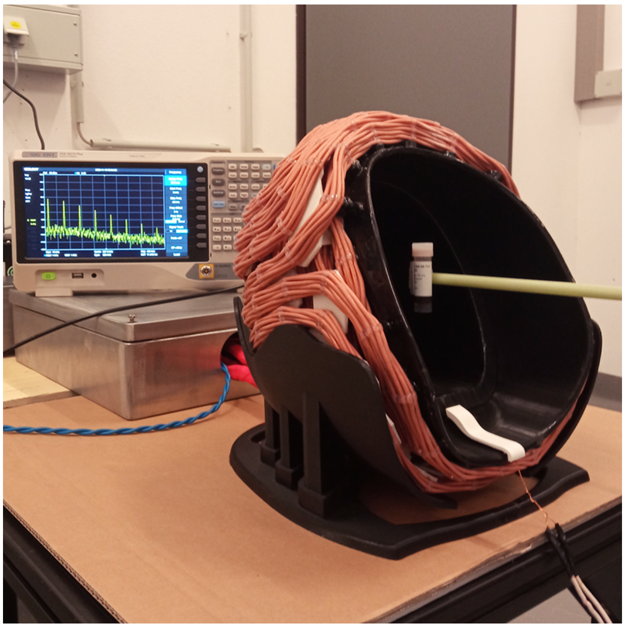

Figure 4: Assembled prototype of a set of power-optimized drive field coils. The spectrum analyzer shows particle signals in a range of 15-400 kHz.

inside the coils. The experimental setup is depicted in Fig. 4. Particle signals were detected in the frequency range from 15 to 400 kHz using a spectrum analyzer. A homebuilt gradiometric coil was used as a receiver.

IV. Conclusions

The developed anatomically adapted drive field coils have a clear advantage over state-of-the-art solenoid/saddle design in terms of power efficiency. By using anatomical information during development, we were not only able to reduce power consumption, but also improve the ergonomics of the device. These factors could be crucial for future clinical applications, especially if MPI systems are planned to be mobile or installed in locations with limited power resources.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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