

Topology Considerations for an Iron-Core Coil Module Field Generator

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Abstract

The selection-field generator of a Magnetic Particle Imaging (MPI) scanner is typically the system's largest power consumer. For potential use in intensive care units, it would be highly desirable to operate MPI scanners from a standard wall outlet without dedicated high-power infrastructure. Several concepts for more efficient selection-field generation have been proposed in recent years. In this work, we propose a novel generator design based on an array of soft-iron core coils arranged at an angle around the scanner bore. This geometry reduces overall electrical power demand while enabling gradient strengths of up to 0.5 T m^{-1} . The design was simulated and optimized using magnetostatic simulations in COMSOL Multiphysics. To ensure reliable modeling of the soft-iron cores, prototype coils were built and their magnetic fields were measured, providing experimental validation of the simulation models.

I. Introduction

Magnetic Particle Imaging (MPI) is a rapidly evolving imaging modality approaching clinical translation [1]. Various design concepts have been proposed to address the issue of increasing power consumption with larger bores, including scanners with different coil topologies as well as approaches using permanent magnets, soft-iron components or superconductors [1]. Building on the core coil module (CCM) based concept based on [2] presented in [3], we investigate a modified geometry that relaxes previous design constraints and enables higher gradient strengths at reduced electrical power.

II. Methods

All simulations are performed in COMSOL MULTIPHYSICS (v6.2, COMSOL AB, Stockholm, Sweden) using the

AC/DC module. By exploiting geometric symmetries, the meshing effort and computation time are reduced. The measured B-H curve of the employed electrical steel (M800-50A) is integrated to model the magnetic response of the soft-iron cores.

To validate the coil model, two identical CCM are simulated and experimentally characterized [3]. They are mounted face to face at a distance of 32.3 cm, driven with identical currents to generate a central field-free point (FFP), and the resulting magnetic field is measured with a spherical Hall sensor array [4]. At the FFP, the field Jacobian is derived and its largest singular value g from simulation and measurement was compared.

The simulated scanner design features an elliptical bore cross section ($a = 30 \text{ cm}$, $b = 35 \text{ cm}$) that accommodates the drive-field coils and a human head (Fig. 1). The elliptical cross section better matches the anatomical head shape, allowing reduced coil-to-head distance and thus

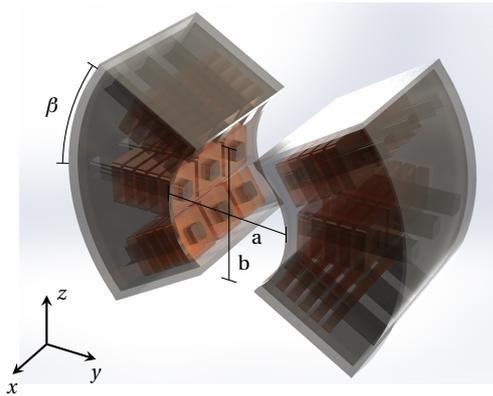


Figure 1: Rendering of the scanner design with 18 soft iron core coils with an outer iron layer, an elliptical bore with semi-axes a and b , and the optimized coil angle β .

a more compact field generator geometry. Eighteen identical iron-core coils are mounted as packs of three with their front face tangential on the bore surface, and their corresponding central face normal pointing toward the x -axis. In each pack the CCM are spaced as closely as mechanically feasible under realistic manufacturing tolerances. An outer electrical steel shell of 1.5 cm thickness surrounds the assembly. The remaining design variable is the CCM stack angle $\beta \in [35^\circ, 55^\circ]$.

For each candidate angle β , the inverse current problem is solved as defined in [2], eqs. (21)-(24). In the notation of that work, the parameters are $\alpha = 0.5$ and $\Delta x = 5$ mm. The optimization minimizes ohmic losses while enforcing a central FFP with a selection-field gradient of $g = 0.22 \text{ T m}^{-1}$. The gradient strength is selected to compare performance with that of the scanners in [5] and [2]. After identifying the optimal β , the same procedure was repeated for FFP offsets along the x -, y -, and z -axes within 16 cm to map the resulting power demand. Additionally, the power consumption for a central FFP with $g = 0.5 \text{ T m}^{-1}$ is calculated.

III. Results and Discussion

Figure 2 (top) compares simulated and measured axial gradients for a pair of iron-core coils. The average deviation is below 1 %, supporting the validity of the coil model used for the subsequent scanner simulations.

The middle plot shows the total power of simulated scanner design for various stack angles β . Although the variation is moderate, a clear minimum appears at $\beta = 42.5^\circ$. Using this angle, power maps for an FFP displaced along the x -, y -, and z -axes are shown at the bottom of Figure 2. At a gradient of 0.22 T m^{-1} , the proposed design requires 45 % less power compared to the field generator in [5] in its operating regime and also enables for the free movement of the FFP in space. For $g = 0.5 \text{ T m}^{-1}$

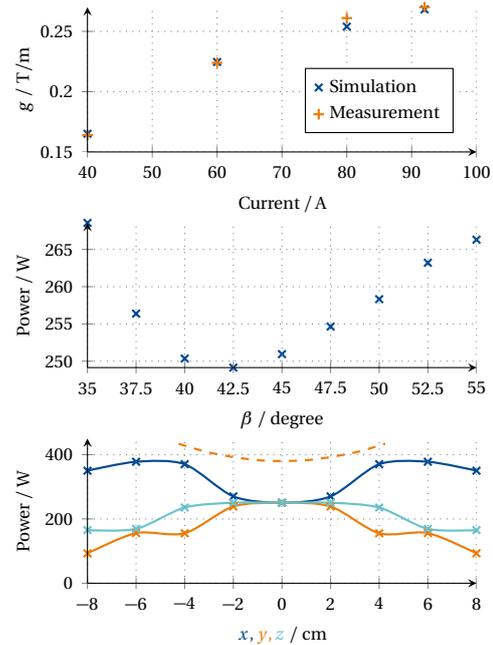


Figure 2: Comparison of the achieved gradient in measurement and simulation data (top), power variation over the coil angle β (middle), and power consumption for FFP displacements with $g = 0.22 \text{ T m}^{-1}$ along the coordinate axes (bottom). The dashed line shows the power consumption of the field generator in [5] for an 8.5 cm FFP movement on the y -axis for comparison.

the system requires about 2.5 kW, still compatible with single-phase wall power and achievable cooling. The field generator design thus offers considerably improved power efficiency over previous selection-field designs and is a step toward bedside MPI systems without special power infrastructure.

Author's statement

Conflict of interest: Authors state no conflict of interest.

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