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Design of a rabbit scale 3D magnetic particle imaging system with amplitude modulation

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Abstract

Magnetic Particle Imaging (MPI) is a fast and sensitive imaging method that can be used to measure the spatial distribution of superparamagnetic iron oxide (SPIO) nanoparticles. To overcome some limitations of general MPI, the Amplitude Modulation MPI (AM MPI), which uses a low-amplitude excitation field combined with a low-frequency drive field, was suggested. In this paper, we present the design of a rabbit scale 3D AM MPI system with a bore size (9 cm). The AM MPI can reach a drive-field field-of-view (DF-FOV) of 4.00 x 4.00 x 8.00 cm^3 and a whole field-of-view (W-FOV) of 6.36 x 6.36 x 8.00 cm^3 at 2.2 T/m.

I Introduction

Magnetic Particle Imaging (MPI) is a fast and sensitive imaging method that can be used to measure the spatial distribution of superparamagnetic iron oxide (SPIO) nanoparticles [1]. Current MPI system mainly suffer from scalability issues that limit their possible applications to small objects. In general MPI that uses a soft magnetic core, it is difficult to enhance the magnetic field gradient for enhanced field-of-view (FOV) because the soft magnetic core generates harmonic distortion, which makes it difficult to acquire the monitoring signals of particles [2, 3]. Furthermore, due to the possibility of unpleasant peripheral nerve stimulation (PNS) [4], the general MPI cannot use a high drive field amplitude, which directly affects the drive-field field-of-view (DF-FOV). In addition, a wide-bandwidth receiver coil is required for general MPI [5].

Therefore, the AM MPI was suggested [2, 6, 7] to solve these limitations of scalability. The AM MPI uses a low- amplitude-high-frequency excitation field combined with a low-frequency-high-amplitude drive field. Thus, the measured signal of AM MPI becomes less sensitive to the effects of the soft magnetic core. Furthermore, it requires only a narrow-band receiver coil, which is easier to implement and is more robust against noise. However, in the previous works [2, 6, 7], the AM MPI systems have only been developed for 1D and with a bore size of 4 cm. These previous AM MPI systems also have a low temporal resolution of MPI [2, 6, 7] due to the utilization of a DC power supply to power the shared coils of the drive and selection fields (SF) to generate and move the Field Free Point (FFP).

In this paper, we present the design of a rabbit scale 3D AM MPI system with a larger bore size (9 cm). Through the use of a soft magnetic core (VACOFLUX 50), we can generate a high gradient field at 2.76 T/m. In this design, in contrast to the previous systems [2, 6, 7], we have separated the drive coils from the selection field coils to implement a higher frequency in order to improve the density of FFP scanning trajectory as well as the temporal resolution. This design promises a larger DF-FOV of 4.00 x 4.00 x 8.00 cm^3 and whole field-of-view (W-FOV) of 6.36 x 6.36 x 8.00 cm^3 at 2.2 T/m as compared to two commercial MPI systems (Magnetic Insight Momentum MPI system and Preclinical Bruker MPI system).

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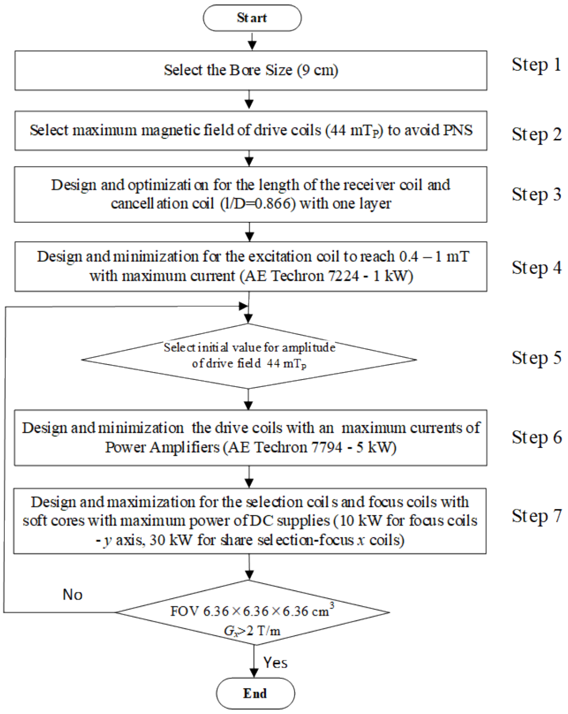

Figure 1: Design flow diagram for the AM MPI system.

II Design methods

The coil design process for the proposed system consists of seven main steps as shown in Fig. 1.

In step 1, the bore diameter is selected as 9 cm for rabbit scale. In step 2, the maximum magnetic field of the drive coils is selected. Since the bore size of 9 cm is similar to the size of human arm, the magnetostimulation threshold for PNS is based on magnetostimulation threshold of the human arm. The threshold of peak-to-peak magnetic field in the human arm is about 72.1 ± 17.5 (mT$_{PP}$) [4], so in this design the maximum amplitude of the drive field is 44 mT$_P$ (or 88 mT$_{PP}$). In step 3, the receiver and cancellation coils are designed according to the optimum relationship between the length l and the diameter D of the coil, which is l/D = 0.866 with one layer. In step 4, the excitation coil is optimized to reach 0.4 - 1 mT with the available power amplifier (AE Techron 7224, 1 kW). In the next step, initial amplitudes of the drive fields are selected according to the maximum amplitude of 44 mTP for 3 axes. Then, the design and optimization of drive coils are processed in step 6 according to the available power amplifier (AE Techron 7794, 5 kW). In step 7, selection coils and focus coils are maximized with the soft core (VACOFLUX 50). The DC power supply for the shared SF and focus field coil in the x-axis is MIGHTY-G Series 30 kW (100A x 300V). The AMETEK SGA 600/17, 10 kW DC power supply is used for the focus field in the y-axis. Since we have a target W-FOV of 6.36 x 6.36 x 6.36 cm^3 at a magnetic gradient greater than 2 T/m, the drive coils, selection coils, and focus coils should be redesigned until the conditions of W-FOV have been satisfied. The summary of the proposed MPI design process is given in Fig. 1. To investigate the influence of coil parameters on the magnetic field and its gradient, simulations were performed using the COMSOL Multiphysics software. The magnetic field generated by the coil was calculated using the AC/DC module of COMSOL with steady state and frequency domain studies. The optimization problem was solved using the COMSOL optimization module.

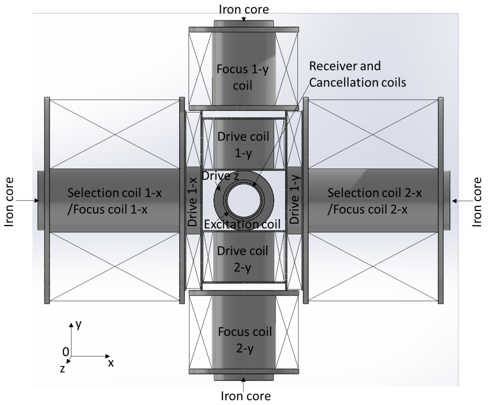

Figure 2: Final design of the rabbit scale 3D AM MPI system.

III Results

The final design of the proposed MPI system is shown in Fig 2. To show the advantages of the proposed design, it was compared with two commercially available MPI systems: Magnetic Insight Momentum MPI system and Preclinical Bruker MPI system [8]. Details of this comparison are shown in Table 1.

Since the maximum gradients and bore sizes of the systems are different, the comparison should be done at the same gradient, which will produce similar spatial resolutions. Thus, the gradient selected for comparison was 2.2 T/m, which produced a MPI spatial resolution of about 1-1.5 mm [9]. At 2.2 T/m, the proposed design has a larger DF-FOV (4.00 x 4.00 x 8.00 cm^3) and W-FOV (6.36 x 6.36 x 8.00 cm^3) as compared to the existing commercially available MPI systems. The frequency of the AM MPI is lower than that of the two commercial systems. However, for the same W-FOV, the AM MPI system due to its larger size of DF-FOV, promises a similar or higher temporal resolution than the two commercial systems. Evaluations of temporal resolution of the proposed system will be performed in the future work.

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Table 1: Comparison of characteristics of the proposed AM MPI design with two commercially available products.

Name	Magnetic Insight Momentum MPI (FFL method)	Preclinical Bruker MPI system (FFP method)	AM MPI (FFP method)
Bore size	6 cm	12 cm	9 cm
Excitation field (mT/kHz)	±15/±0/±15 @ 45 kHz	±14/±14/±14 @ 25 kHz	0.4-1 @ 40 kHz
Drive fields in x,y, and z-axes (mT/kHz)	±15/±0/±15 @ 45 kHz	±14/±14/±14 @ 25 kHz	±44/±22/±44 @ 0.002-2 kHz
Focus field in x/y/z-axes (mT)	±190/±0/±190	±18/±18/±142	±72/±66/±0
Maximum gradient (T/m)	6.2/0/-6.2	2.5/-1.25/-1.25	2.76/-1.38/-1.38
DF-FOV at maximum gradient	0.48 x 0.48 cm^2	1.12 x 2.24 x 2.24 cm^3	3.19 x 3.19 x 6.38 cm^3
W-FOV at maximum gradient	5 x 3.75 x 6.61 cm^3	2.56 x 5.12 x 8.96 cm^3	3.19 x 6.38 x 6.38 cm^3
DF-FOV at 2.2 T/m	1.36 x 2.72 cm^2	1.27 x 2.54 x 2.54 cm^3	4.00 x 4.00 x 8.00 cm^3
W-FOV at 2.2 T/m	5 x 3.75 x 10 cm^3	2.91 x 5.82 x 10.18 cm^3	6.36 x 6.36 x 8.00 cm^3

IV Conclusions

Using AM MPI we can overcome the scalability issues of general MPI and enable scanning of larger animals. The proposed AM MPI is used to reach a 6.36 x 6.36 x 8.00 cm^3 W-FOV. However, MPI imaging tests of SPIO particles should be performed to verify the usefulness of the proposed design in future works.

Author's Statement

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