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Simulation of a hand-held magnetic particle imaging device utilizing triangular waveform scanning

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Abstract

Magnetic particle imaging (MPI) is an emerging molecular imaging technique, and one of the focus of current research is the imaging devices for human applications. Both closed and open systems face limitations in terms of spatial and power constraints, affecting the detection of large volume. Hand-held MPI device is the representative of low power consumption in MPI devices. It can provide flexibility in human imaging due to the compact size. Current hand-held device consist of signal detection component and mechanical movement component, lacking a gradient field within the device itself. This limitation significantly impacts the resolution and scanning time of hand-held device. Here, we propose a new hand-held device design for field free point generation and movement. The feasibility of the device is verified by simulation. It can scan a 20 mm × 20 mm area at a depth of 8 mm without the movement. Furthermore, due to the small impedance of coils, triangular wave scanning can be employed to enhance trajectory uniformity during the process.

I. Introduction

Magnetic particle imaging (MPI) is a medical imaging technology with clinical prospect [1]. The design and development of various MPI devices has always been a key content in this field. Currently, imaging devices for small animals have achieved high performance, prompting a shift in focus toward the design of devices suitable for human-scale imaging. However, one of the key issues currently preventing MPI from being used in humans is the lack of low-power devices suitable for use in humans [2]. Whether in a closed or open device structure, the power required to expand the imaging area to the human body scale increases exponentially. Besides, high gradients are required in order to ensure high imaging resolution for human-scale devices, which inevitably leads further to high power for the selection coil and drive coil. The high gradients and associated high power have a significant impact on the stability of the device. Heat generation becomes a more pronounced concern when

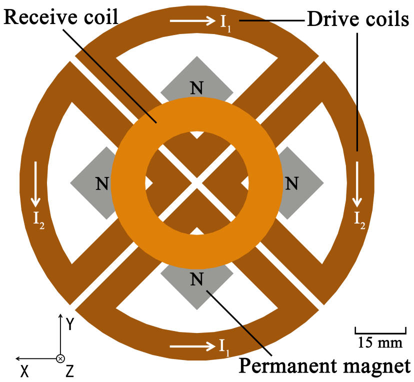

Figure 1: Schematic diagram of permanent magnets and coils for the hand-held MPI device.

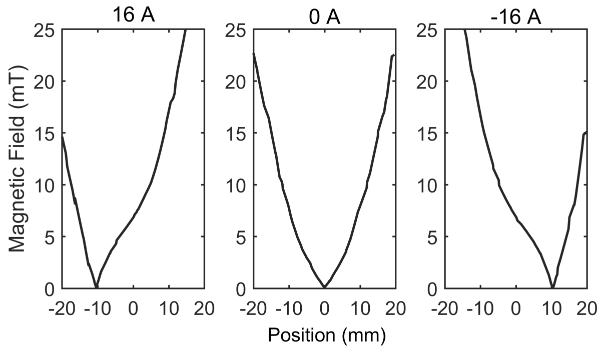

Figure 2: X direction distribution of magnetic field strength when different currents are applied.

the device operates for extended periods. In summary, expanding current common MPI device types to human body scale poses significant challenges [3].

Hand-held MPI device is the representative of low power consumption in MPI devices [4]. Because of its lightweight structure, doctors can use mobile device methods to scan most areas of the body. Hand-held devices typically feature a single-sided structure. single-sided MPI, as a category within MPI devices, is named for its placement of all coils or permanent magnets on the same side of the field of view (FOV) [5]. Existing single-sided MPI devices include FFP and FFL types [6, 7]. If the dimensions of single-sided MPI are designed to be smaller, it can be developed into a hand-held MPI device. However, ensuring imaging depth and imaging quality while reducing the size is a crucial challenge in the development of hand-held MPI.

In this paper, a hand-held MPI device containing permanent magnets and coils is introduced. The magnetic field in the space generated by the device was simulated. In addition, the original location and movement of the FFP validated the feasibility of the device. Most of the existing MPI devices use sine wave excitation. However, a triangular waveform excitation used to shift the FFP is more uniform in the scanning trajectory than sine wave [8]. Due to the small impedance of coils, the triangular wave scanning can be employed in this device.

II. Material and methods

Four permanent magnets of the same polarity are placed in parallel to generate a selection field and FFP. The generated magnetic field is symmetric, using the position of the unilateral FFP as the center of the FOV. The height of the FFP and the gradient of the selection field are determined by the size and spacing of the permanent magnets. Four fan-shaped drive coils are located on the outside of the four permanent magnets. The circular receive coil is used to receive the magnetization response signal of magnetic nanoparticles (MNPs). The direct feed-through effect in this device is relatively small, so compensation coils are not considered necessary. Positions of the permanent magnets and coils of the hand-held device are shown in Figure 1. Each of the two drive coils is a group. A group of drive coils are fed with opposite currents, which can cause the FFP to move in one direction. Two groups of drive coils pass current with different frequencies to make the FFP scan in accordance with a specified trajectory, such as a Cartesian trajectory or a Lissajous trajectory.

When frequencies in drive coils reach the kHz level, there is no need to use an additional high frequency excitation coil to make the MNPs produce high frequency signals [1]. In order to ensure the uniformity of the scanning trajectory, Lissajous trajectory was chosen. In order to further improve the uniformity of the central and edge regions of the FOV, the current waveforms within the drive coils are selected as triangular waves. Since the impedance of the coils is small, impedance matching can be not required, and the device can be driven using high-frequency triangular waves [9].

III. Results and discussion

Four drive coils have outer and inner radii of 50 mm and 42 mm in simulation. The material of the permanent magnets is N42, and the size of each permanent magnet is 15 mm × 15 mm × 5 mm. The receive coil, positioned along the negative Z-axis relative to drive coils, features inner and outer diameters of 20 mm and 40 mm, respectively. The FOV is located 8 mm along the negative Z-axis of the drive coils, with a magnetic field gradient of 0.75 T/m. At the beginning of the scan, there is no current in four drive coils, and the FFP is located in the center of the FOV. When the currents in the first group of drive coils reach 16 A and -16 A, respectively, the FFP can be moved 10 mm away from the center position. The selected drive frequency is 5 KHz and peak current is 16 A, and the corresponding maximum power is 1340 W. Taking X direction scanning as an example, when the instantaneous current is 16 A, 0 A and -16 A, the magnetic field distribution of the FOV is shown in Figure 2.

In this hand-held device, the distance between the permanent magnets, the radius of the drive coils, and the current required to pass through the drive coils are all related. As the distance between permanent magnets decreases, the gradient of the selection field increases, but the distance of the FFP from the coils decreases, which limits the depth of the scan. In addition, as the gradient increases, the current conversion efficiency of the drive coils needs to increase, that is, turns of the coils needs to be increased. Therefore, this work mainly introduces the structure that can generate and move the FFP. When it is necessary to determine the specific scanning depth and resolution, the size of permanent magnets and coils need to be more detailed design.

IV. Conclusions

This paper presents a new hand-held MPI design. In the simulation, two-dimensional scanning of the 20 mm × 20 mm area can be achieved by the proper arrangement of the permanent magnets and coils. For specific scanning needs, the size of permanent magnets and coils can be changed to improve scanning resolution or depth. The device enables fast imaging of the distribution of MNPs. Therefore, it is better suited for applications requiring higher resolution and imaging speed. Regarding its hand-held capability, we believe this device could be employed for rapid tumor screening and intraoperative guidance for tumor resection.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

References

[1] B. Gleich and J. Weizenecker. Tomographic imaging using the nonlinear response of magnetic particles. *Nature*, 435(7046):1214–1217, 2005, doi:10.1038/nature03808.

[2] M. Gräser, F. Thieben, P. Szwargulski, F. Werner, N. Gdaniec, M. Boberg, F. Griese, M. Möddel, P. Ludewig, D. Van De Ven, *et al.* Human-sized magnetic particle imaging for brain applications. *Nature communications*, 10(1):1936, 2019, doi:10.1038/s41467-019-09704-x.

[3] J. Borgert, J. D. Schmidt, I. Schmale, C. Bontus, B. Gleich, B. David, J. Weizenecker, J. Jockram, C. Lauruschkat, O. Mende, *et al.* Perspectives on clinical magnetic particle imaging. *Biomedizinische Technik/Biomedical Engineering*, 58(6):551–556, 2013, doi:10.1515/bmt-2012-0064.

[4] S. Azargoshasb, L. Molenaar, G. Rosiello, T. Buckle, D. M. van Willigen, M. M. van de Loosdrecht, M. M. Welling, L. Alic, F. W. van Leeuwen, A. Winter, *et al.* Advancing intraoperative magnetic tracing using 3d freehand magnetic particle imaging. *International journal of computer assisted radiology and surgery*, 17:211–218, 2022, doi:10.1007/s11548-021-02458-2.

[5] T. F. Sattel, T. Knopp, S. Biederer, B. Gleich, J. Weizenecker, J. Borgert, and T. M. Buzug. Single-sided device for magnetic particle imaging. *Journal of Physics D: Applied Physics*, 42(2):022001, 2008, doi:10.1088/0022-3727/42/2/022001.

[6] K. Gräfe, A. von Gladiss, G. Bringout, M. Ahlborg, and T. M. Buzug. 2d images recorded with a single-sided magnetic particle imaging scanner. *IEEE transactions on medical imaging*, 35(4):1056–1065, 2015, doi:10.1109/TMI.2015.2507187.

[7] C. McDonough, D. Newey, and A. Tonyushkin. 1-d imaging of a superparamagnetic iron oxide nanoparticle distribution by a single-sided ffl magnetic particle imaging scanner. *IEEE transactions on magnetics*, 58(8):1–5, 2022, doi:10.1109/TMAG.2022.3151710.

[8] T. Knopp, S. Biederer, T. Sattel, J. Weizenecker, B. Gleich, J. Borgert, and T. Buzug. Trajectory analysis for magnetic particle imaging. *Physics in Medicine & Biology*, 54(2):385, 2008, doi:10.1088/0031-9155/54/2/014.

[9] Z. W. Tay, P. W. Goodwill, D. W. Hensley, L. A. Taylor, B. Zheng, and S. M. Conolly. A high-throughput, arbitrary-waveform, mpi spectrometer and relaxometer for comprehensive magnetic particle optimization and characterization. *Scientific reports*, 6(1):34180, 2016, doi:10.1038/srep34180.

10.18416/ijmpi.2024.2403043