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Rotation Unit for Permanent Magnet Based MPI Devices

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Abstract

For the utilization of the magnetic field of rotating Halbach cylinders in MPI scanners, a rotation unit is required which houses the used permanent magnets and allows their rotation. The setup proposed here allows the concentric arrangement and individual rotation of four Halbach cylinders, whose purely mechanic agitation allows the movement of the field-free region through the field of view. Based on the requirements for such a rotation system, basic design approaches are presented and compared. Initial strength calculations and further simulations were performed on the resulting constructive concept, which, upon implementation, forms the basis for almost purely mechanical MPI scanners.

I. Introduction

In MPI the spatial encoding relies on a selection field featuring a linear field gradient, which forms a field free region (FFR). Only particles inside this FFR can change their magnetisation and contribute to the received particle signal. Therefore, to scan an area or volume the FFR has to be moved on a designated trajectory by the so called drive field. One challenge in the implementation of MPI scanners is the power consumption when electrically generating the needed magnetic fields. To counter this problem several scanner concepts featuring permanent magnets as field generators have been proposed [1, 2]. Previously a scanner concept consisting of four concentrically nested Halbach-cylinders was presented [3], proposing a mainly mechanical MPI scanner with high flexibility. The concept is based on two outer rings of Halbach-cylinders in quadrupole configuration forming a field free line (FFL) with adaptive gradient strength, and two inner cylinders in dipole configuration as adaptive homogeneous drive field . Based on the FFL, a field free point only in the central cylinder plan can be used for 2D projection imaging. The Rotation of the dipole rings in opposite directions shifts the FFP on an one-dimensional path. By rotating the whole setup, while keeping the reversely rotation on the dipoles in place, a two-dimensional radial trajectory can be achieved (Figure 1). To drive the proposed system a rotation unit that allows the independent rotation of four Halbach-cylinders is necessary. This paper aims to show a construction concept of such a drive unit.

II. Methods and materials

To realize the desired drive, certain requirements must be satisfied. This concerns in particular the holding of the permanent magnets, the absorption of forces, the

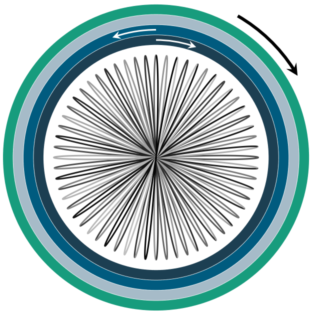

Figure 1: Representation of the concentric Halbach cylinders (dipoles: ▮, ▮; quadrupoles: ▮, ▮) to be rotated, as well as the representation of the resulting, two-dimensional radial trajectory. Within the trajectory, each line ($N = {}^{f_d}/_{f_q}$) resulting from the rotation of the dipoles and bended by the rotation of the whole setup is colored differently. (cf. [4]).

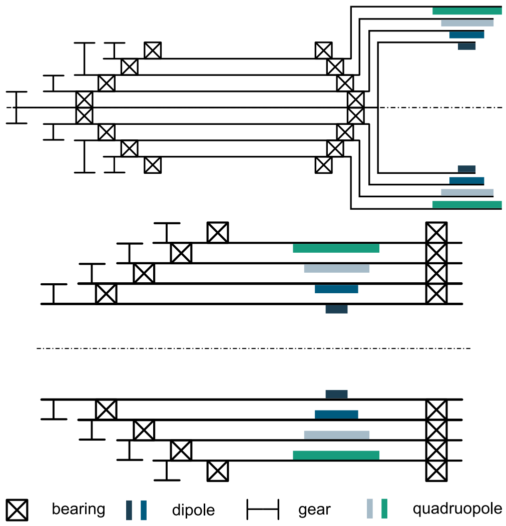

Figure 2: Conceptual bearing arrangements for the rotation unit and corresponding magnet positions. Top: single sided floating bearing; Bottom: two-sided bearing

bearings and the rotational speeds to be achieved. The exemplary chosen dipole frequency of $f_d = 100\,\mathrm{Hz}$ [4] was set as upper limit for the construction considerations. According to [4] [5], the coarsest sampling using a radial trajectory results in a period length of $T_R = 0.3\,\mathrm{s}$ at a frequency of the complete setup of $f_q = {}^{10}/_3\,\mathrm{Hz}$.

The constructional requirements for the rotation unit demands the accommodation of the presented Halbach-cylinders, a variable rotation of the individual components with $|f| \leq 100\,\mathrm{Hz}$, a natural frequency of the system significantly higher than the target rotation frequency in order to prevent a resonance issue and general compliance with design guidelines of mechanical engineering. Two bearing arrangements are suitable for the suspension of the Halbach-cylinders to be rotated: a two-sided bearing or a single sided floating bearing (cf. Figure 2).

With a two-sided bearing, the permanent magnets would be placed in between the bearings, resulting in lower bearing forces due to shorter lever arms and wider force distribution. Additionally this arrangement would allow for a continuous bore, which might be advantageous for various measurement applications.

For the single sided floating bearing concept the main force application point would be outside of the two bearings, resulting in higher bearing forces. However, unlike the two-sided arrangement, the bearing sizes are not necessarily defined by the dimensions of the cylinders and therefore smaller bearings can be used. The maximal permitted rotation speed of ball bearings is limited, among other things, by the friction of the rolling elements. As the bearing diameter increases, the speed of the balls increases, so friction and heat generation increases accordingly (cf. [6]). Therefore, the floating bearing concept allows the operation at significantly higher speeds. In addition, access to the magnetic holder is much easier in this approach, since there is no need to disassemble the whole setup including the bearings. A simpler exchange of the magnet configuration is possible this way, so that the setup has a higher flexibility and can thus also serve as a basis for other imaging concepts. Due to the spatial separation of shafts and magnets, care must be taken to place the bearing as close as possible to the outside mass elements. This is necessary to reduce the deflection of the shafts and keep the critical speed as high as possible.

The individual bearings must each be adapted to the relative speed that occurs between the rotating shafts. The maximum relative rotational speed is $2 \cdot f_d$ in the bearing between the dipoles. The relative speed between dipole and quadrupole can be specified to $f_d - f_q$. Since the quadrupoles do not have to rotate against each other during the described imaging sequence, the relative speed equals zero, while the speed of the outer bearing corresponds to the quadrupole rotation f_q.

Due to the high speeds, an adjusted bearing in O-arrangement is most suitable, as a stiff and free of play suspension can be achieved. Vibrations can be minimized by the preload used in this bearing concept, so that attrition is reduced and smother running can be achieved. The larger support distances in an O-arrangement allow for the absorption of larger tilting moments created by the one-sided mass load, but it is important to ensure that the permissible deformation ($d_{\mathrm{allowed}} < {}^{l}/_{3000}$) is not exceeded which would result in imbalances. [7–9]

Using the described single sided floating bearing concept, the permanent magnets needed for the imaging process can be placed in hollow shafts on one side of the rotation unit, while the torque transmitting elements connecting the shafts via a gearing to motors are located on the other side (cf. Figure 3).

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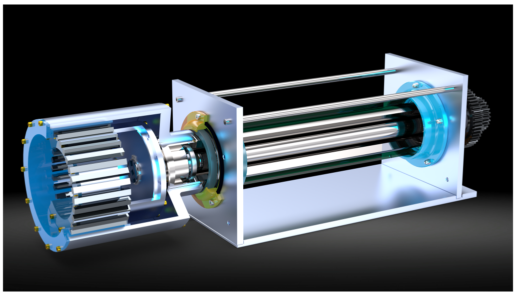

Figure 3: Construction concept for a prototype containing two of the four panned shafts for rotating the dipoles.

III. Results

The prior considerations resulted in a construction concept of the floating bearing arrangement, that combines the described sub-concepts and forms the basis for further simulations and strength calculations. Since most data on strength and tolerances are available for steels, the distance of the rotating shafts from the imaging plane is comparatively large and high frequency signals can be further shielded, an austenitic corrosion-resistant steel (EN 10088-3 - 1.4301) with a permeability of $\mu_r < 1.3$ [10] was selected as the material for the implementation and calculation.

To check the feasibility of implementation, the maximum occurring torsion stress was calculated at the critical point of the shaft-hub connection to the magnetic holders, with a safety factor of $S > 6$ compared to the permissible shear stress of the material. [7] Based on this conceptual design, the critical parameters resonance frequency and deflection were approximately calculated and simulated. The lowest simulated resonance frequency of $f_{\text{res}} = 539\,\text{Hz}$ occurring in the smallest shaft is over five times higher than the target excitation frequency, so that the resonance case will be avoided. The deflection was simulated for the whole setup of gear, shaft and magnet holder containing the chosen magnet configuration. For the innermost dipole assembly, the maximum deflection is 1.107 µm occurring on the outermost edge of the magnet holder, while the deflection of the shaft itself is below 0.665 µm. With a maximal length of 774 mm the mechanical guidelines suggest a deflection limit below 0.258 mm.

IV. Discussion and Outlook

Based on four concentric shafts the presented MPI scanner design is intended to enable the fast rotation of four Halbach-cylinders and thus form the basis for an almost completely mechanical scanner. The presented initial concept includes some main calculations and simulation results, but further constructive aspects need to be considered and reviewed before the full implementation. This includes the calculation of the correct preload force as well as a durability analysis, the frictional torque, the lubrication, the generated heat and possible additional forces through eddy currents in the rotating system. An analysis of occurring imbalances and possibilities of their measurement and compensation must be carried out. For safe operation, a suitable housing must be developed to protect users against contact with the moving parts and to absorb occurring vibrations. Basic concepts for the actuation, including a suitable gearing, are currently reviewed and need to be adapted to a motor, break and rotary encoder. This gearing will also allow the controlled adjustment of the angle between the quadrupoles and therefore the gradient used for the imaging [3]. With the integration of a transmit and receive chain, the presented concept of a rotation unit forms the basis for a mainly mechanical MPI-Scanner.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

References

[1] M. Weber, J. Beuke, A. Von Gladiss, K. Gräfe, P. Vogel, V. C. Behr, and T. M. Buzug. Novel field geometry using two halbach cylinders for ffl-mpi. *International Journal on Magnetic Particle Imaging*, Vol 4:No 2 (2018), 2019, doi:10.18416/IJMPI.2018.1811004.

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

[3] A. C. Bakenecker, J. Schumacher, P. Blümler, K. Gräfe, M. Ahlborg, and T. M. Buzug. A concept for an mpi scanner with halbach arrays. *International Journal on Magnetic Particle Imaging*, pp. Vol 6 No 2 Suppl. 1 (2020), 2020, doi:10.18416/IJMPI.2020.2009008.

[4] A. C. Bakenecker, J. Schumacher, P. Blümler, K. Gräfe, M. Ahlborg, and T. M. Buzug. A concept for a magnetic particle imaging scanner with halbach arrays. *Physics in Medicine & Biology*, 65(19):195014, 2020, doi:10.1088/1361-6560/ab7e7e.

[5] T. Knopp, S. Biederer, T. Sattel, J. Weizenecker, B. Gleich, J. Borgert, and T. M. Buzug. Trajectory analysis for magnetic particle imaging. *Physics in Medicine and Biology*, 54(2):385–397, 2008, doi:10.1088/0031-9155/54/2/014.

[6] DIN ISO 15312:2019-04, Wälzlager - Thermische Bezugsdrehzah - Berechnung (ISO 15312:2018). doi:10.31030/3035417.

[7] K.-H. Grote, B. Bender, and D. Göhlich, Dubbel - Taschenbuch für den Maschinenbau. Berlin Heidelberg New York: Springer-Verlag, 2018, doi:10.1007/978-3-662-54805-9.

[8] H. Wittel, D. Muhs, D. Jannasch, and J. Voßiek, Roloff/Matek Maschinenelemente. Springer Fachmedien Wiesbaden, 2015, doi:10.1007/978-3-658-09082-1.

[9] G. Niemann, H. Winter, and B.-R. Höhn, Maschinenelemente - Konstruktion und Berechnung von Verbindungen, Lagern, Wellen. Berlin Heidelberg New York: Springer-Verlag, 2005, doi:10.1007/b137557.

[10] P. Zacharias, Magnetische Bauelemente, 1st ed. Springer Vieweg, Wiesbaden, 2020, doi:10.1007/978-3-658-24742-3.