

Orthogonality characterization of 3D Helmholtz coil fields

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Summary:

We present a new method for the characterization of 3D Helmholtz coils with respect to their field orthogonality errors. It is based on 3D field sensing inside the homogeneity region using conventional 3D Hall sensors that need to be precisely orthogonality calibrated in a first step. Repeated measurements with different such sensors are used to confirm the algorithmically determined 3D coil field tolerances. Upon finding discrepancies, we discovered environmental influences affecting the determination of the coil orthogonality angle errors and propose means to minimize their impact.

Keywords: Helmholtz coil characterization; 3D Hall sensors; Hall sensor tolerances; Helmholtz coil magnetic field tolerances; piezo-Hall effect

Introduction

The magnetic field generated by a system of Helmholtz coils is subject to mechanical manufacturing tolerances, in case of a 3D system in particular the alignment of the three coil pairs relative to each other. Similarly, also multi-axis sensor systems need a precise assembly of three orthogonally placed Hall plates, each measuring the perpendicular field projection. Any angle deviations from orthogonality of Hall plates or coil arrangements lead to incorrectly measured or generated magnetic fields. As we show below, neither topic should be considered isolated from the other as discrepancies in orthogonality of coils can be determined from precisely calibrated sensors and vice versa.

A Helmholtz coil is made of a co-axial pair of air coils, separated by precisely the radius of the respective coils generating a homogeneous field in their center. An arbitrary field orientation is achieved by superposition of three such fields from three orthogonally placed pairs of coils.

Instead of conducting a magnetic field inversion, typically having many degrees of freedom to determine the coil assembly orientation from multiple simultaneous field measurements and to potentially correct for coil misalignments, we rather aim at a coil field characterization in terms of its orthogonality errors, irrespective of the particular mechanical tolerances in the three-axis coil assembly responsible (e.g. by angular deviation or center offsets either of the coil pairs themselves or between those pairs). An alternative rigorous treatment of the field of 3D coil systems considering its source with the intricate details down to

the level even of the geometry of conducting elements for specific winding technologies has been elaborated in [1].

In [2] a calibration scheme for a three-axis Helmholtz coil via optical methods by gauging the assembly with a laser tracking routine is presented. [3] describe the calibration of a triaxial Helmholtz coil via a rotating magnetic field scheme using a minimization procedure for an objective orthogonality angle deviation function. A calibration method for a planar sensor array in a 3D Helmholtz coil system using machine learning based sensor vector correction is presented in [4]. We on the other hand use a single 3D sensor per measurement and relate the Hall plate sensor output to the three coil field components in our calibration such that the field generated in the coil system can be corrected for the coil misalignment by adjusting the nominal currents applied to the three coils.

Methods

Our scheme allows for arbitrary orientational placement of a 3D Hall sensor into the homogeneity region of the coil system. It requires priorly determined 3D sensor orthogonality angle errors or equivalently, the Hall plate orientations \mathbf{n}_1 , \mathbf{n}_2 and \mathbf{n}_3 and sensitivities as input into the algorithm. Supplying current to each of the coils separately and measuring the sensor outputs on the three Hall plates, we obtain a signal matrix $O_{ij} = \mathbf{n}_i \cdot \mathbf{B}_j$, $(i, j) = 1, 2, 3$ for the projection of each coil field onto each of the Hall plates. The background field and sensor offsets are corrected for in the signal matrix, recorded a couple of thousand times to average out sensor noise. We

solve for the three coil fields in the relation between fields and Hall plate signals,

$$\begin{pmatrix} n_{xx} & n_{xy} & n_{xz} & 0 & 0 & 0 & 0 & 0 & 0 \\ n_{yx} & n_{yy} & n_{yz} & 0 & 0 & 0 & 0 & 0 & 0 \\ n_{zx} & n_{zy} & n_{zz} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & n_{xx} & n_{xy} & n_{xz} & 0 & 0 & 0 \\ 0 & 0 & 0 & n_{yx} & n_{yy} & n_{yz} & 0 & 0 & 0 \\ 0 & 0 & 0 & n_{zx} & n_{zy} & n_{zz} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & n_{xx} & n_{xy} & n_{xz} \\ 0 & 0 & 0 & 0 & 0 & 0 & n_{yx} & n_{yy} & n_{yz} \\ 0 & 0 & 0 & 0 & 0 & 0 & n_{zx} & n_{zy} & n_{zz} \end{pmatrix} \begin{pmatrix} B_{xx} \\ B_{xy} \\ B_{xz} \\ B_{yx} \\ B_{yy} \\ B_{yz} \\ B_{zx} \\ B_{zy} \\ B_{zz} \end{pmatrix} = \begin{pmatrix} O_{xx} \\ O_{yx} \\ O_{zx} \\ O_{xy} \\ O_{yy} \\ O_{zy} \\ O_{xz} \\ O_{yz} \\ O_{zz} \end{pmatrix}$$

and obtain angles $\alpha = \angle(\mathbf{B}_x, \mathbf{B}_z)$, $\beta = \angle(\mathbf{B}_x, \mathbf{B}_y)$ and $\gamma = \angle(\mathbf{B}_y, \mathbf{B}_z)$, specifying the deviation from orthogonality. Different sensors, each calibrated for their own orthogonality errors are used to re-evaluate the coil orthogonality and provide an average and spread of the coil calibration results.

Results: Humidity and temperature effect on the sensor orthogonality

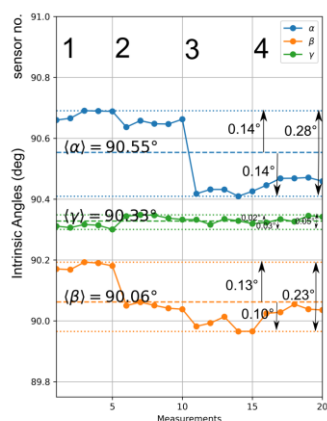


Figure 1: Orthogonality error results based on 5 measurements with 4 different 3D Hall sensors.

Substantial deviations from orthogonality of $\sim 1^\circ$ between results obtained from different sensors were found in attempts to calibrate several coil systems, indicating a systematic error in the procedure. While repeated calibrations with one sensor confirmed the previous outcomes, the results of different sensors did not match with one another. When therefore repeating the sensor calibration in a precalibrated Helmholtz coil system (specified with an orthogonality accuracy $< 0.1^\circ$) based on a computation scheme like the one described above but swapped roles of known coil field orientations and yet to be determined Hall plate orientations), we found those sensor calibration measurements to vary from day to day by as much as $\sim 1^\circ$ with fluctuating environmental parameters of humidity and temperature. We addressed the issue with repeated sensor calibrations in varying environmental conditions to generate a table of calibration measurements depending on temperature and humidity. When performing the actual coil orthogonality characterization, values for sensor orientations n_i were determined from a 2D interpolation of our sensor calibration table, representation plate orientations as to be expected in those specific humidity and temperature conditions. With the corrected inputs, the coil

orthogonality could be significantly improved and specified within a range of $\pm 0.15^\circ$ around the average based on the results from all the different sensors used, see Fig. 1.

Discussion

An algorithm and measurement procedure for the orthogonality calibration of a 3-axis Helmholtz coil were discussed. The procedure is statistical only in the way that measurements are to be repeated to minimize the impact of sensor noise on the signal, while the fields are computed in a deterministic way.

A major realization was the impact of humidity and temperature on the sensors via mechanical stresses onto the sensing element packages. The effect of mechanical stresses on the accuracy of 3D Hall sensors and a means of compensation via a cointegrated piezoresistive stress sensors was reported only recently in 2024 [5] and provides an alternative to our interpolation scheme, once this sensor technology becomes commercially available.

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