3-Axis Magnetic Field Mapping in System Design Validation

Dr. Mark Harradine, Ph. D; John Maisch; Richard Stelter

Dexter Magnetic Technologies

Abstract

The advent of the PC as a commonplace design tool has greatly enhanced the magnetic system designer's ability to predict the behavior of magnetic systems. However, there is still, as in any science, a fundamental need to validate a design by measuring actual performance of the manufactured device.

The purpose of any system validation is two-fold:

1) Does the device meet its required specifications?

2) Do the results relate accurately to the software determined prediction? (This is probably more important in the long term).

The critical extraction of information using a 3-axis field mapper can serve to improve designs and gain consistency in results. As such, it is an important tool in the design engineers box, as well as a quality assurance device.

Introduction

A single piece of magnetic material can easily be validated by Helmholtz tests, Gaussmeter readings or any number of other tests. However, there is no test procedure for magnetic systems and assemblies, other than whether the system performs the work required of it. To improve magnetic systems it is important to be able to measure the performance of the magnetic system independent of the function it is to perform. The data can then be used to validate the relationships between field and function, and devise improvements.

A 3-axis magnetic field mapper, as its name implies, is a tool that allows the user to map a magnetic field at any point, over any surface or throughout any volume in space. The "3-axis" part of the name refers to the ability to move a 3-axis Hall probe through a three dimensional volume while capturing the three orthogonal components of magnetic vectors at designated points in that volume, so a magnetic field profile can be plotted.

Measurement of the 3 Cartesian components of magnetic flux density can be simply achieved by using three orthogonally arranged Hall elements. A probe with three such elements is placed on an actuated arm, the arm being capable of incremental three-axis motion by virtue of linear actuators on each axis. The entire assembly is built with non-magnetic materials. Extruded Aluminum components are excellent for this purpose as they offer rigidity and are non-magnetic.

The whole system is controlled by a PC, which can be mounted either on top of, or nearby the system to be mapped. (It is wise to use an older monitor as the fields from magnetic devices can distort the image significantly. Make sure there is a "De-Gauss" control on the monitor).

While simple in concept, there are some subtleties of design that can enhance both the accuracy and utilization of the mapper.

Design of 3-Axis Magnetic Field Mapper

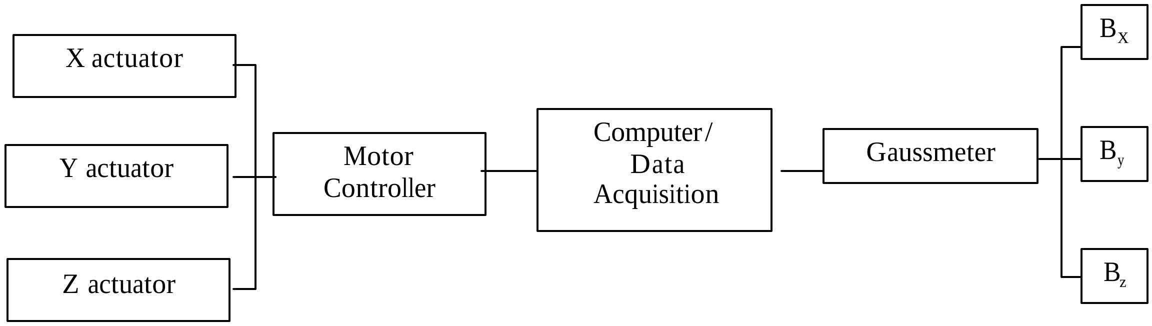

Figure 1: Schematic of 3-Axis Magnetic Field Mapper

Figure 1 shows the basic schematic of any field mapping system. One can see these items clearly in the Dexter Magnetic Technologies 3-Axis field mapper below.

Figure 2: Dexter Magnetic Technologies 3-Axis field Mapper.

It is not the intent of this paper to analyze the construction of the mapping tool, but there are some important design aspects to consider. The physical size of the devices to be mapped is a first consideration. The authors have determined that the best compromise between mapped volume and positional accuracy (tolerance) is achieved with actuators that have a range of around 500-600 mm. This is sufficient for most magnetic systems, but it has been necessary to use four or five overlapping mapping sessions to completely map some of the larger magnet systems. Another critical aspect in the design of a mapper is to ensure that when the probe is taking measurements at the various points, the probe tip is stationary. It may be necessary to employ a specific drive waveform to control actuator acceleration and deceleration to reduce the vibration of the probe tip, or damp vibration by other means.

Taking Measurements

The accuracy to within which one can make a field measurement is determined by the size and position of the three hall elements within the probe tip. Clearly, all three hall elements cannot occupy a single point in space. There is therefore a limit on the resolution of the field map that can be achieved. Consider the layout of hall elements in the diagram below.

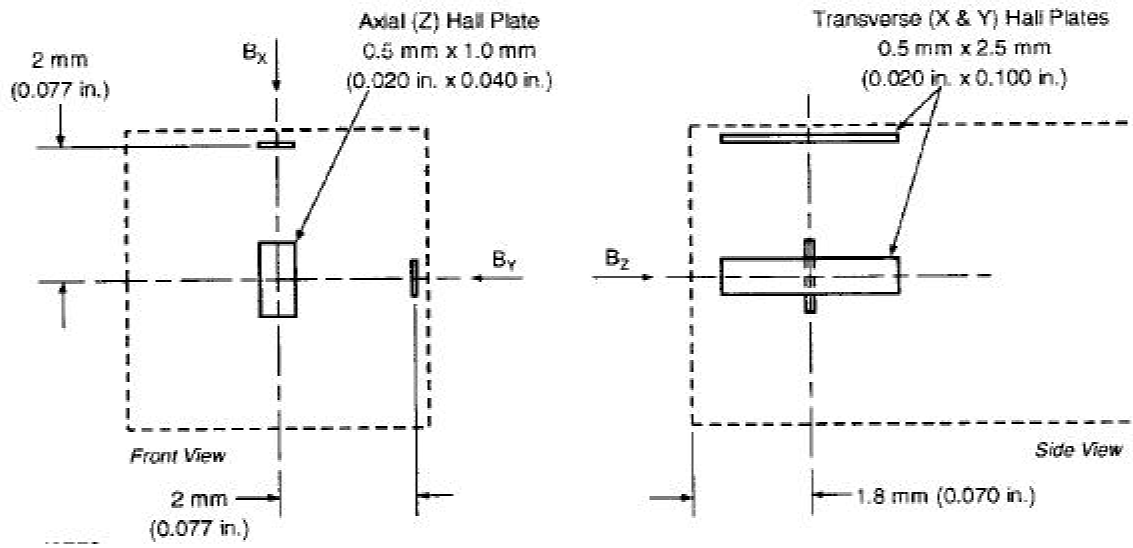

Figure 3: Example of layouts of hall elements within a 3-axis hall probe.

As a general rule, the limit for field resolution is twice the largest separation of elements; for the example in Figure 3, the best resolution would be 4mm.

This generally this does not prove to be a problem, but for specific magnet systems, one may encounter other limitations. For instance, in high gradient magnetic devices, where the field decays or increases very quickly over a certain region, there may be resolution problems. In general though, the results are accurate enough to validate software predicted values and profiles, and for QC purposes.

One method that may be employed in order to achieve a higher resolution is to map a region 3 times. In each succeeding session, the probe is positioned to compensate for specific Hall element locations within the probe, (most probe manufacturers will include this information in their literature).

Adding value (for yourselves and your customers)

The 3-axis magnetic field mapping tool is an essential part of the design process, as well as a QC tool. Typically, the production of a permanent magnet dipole will follow these steps.

1) Receive request for engineering
2) Determine Feasibility
3) Magnetic modeling, (BEA or FEA)
4) Production prints, manufacture and assemble
5) MAGNETIC FIELD MAPPING
6) Shipping

Once the request for engineering has been received, a feasibility study is done. There are calculation tools available, (in Excel spreadsheet format), which will allow for rapid determination of field values for simple configurations of magnets. Such tools are useful to establish approximate values. If further engineering seems feasible, then typically a design engineer will create a boundary or finite element model. These tools are excellent at determining field solutions for complex geometries, but their true value is only achieved when the user is able to correctly set parameters. The magnetics design engineer will look for symmetry, anti-symmetry and periodicity in the device. By setting symmetric or periodic boundaries, seemingly complex geometries can be simplified within the computer software. The software, after solving the problem, will be able to generate almost any interpretation of the field solutions for the end user.

The computer software will generate solution for a perfectly constructed device, with perfectly consistent material, as seen in Figure 4 below.

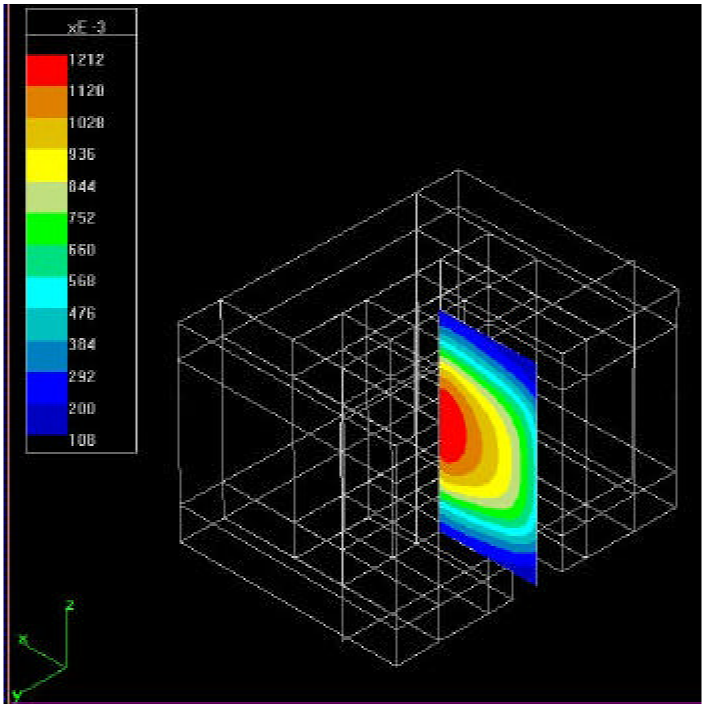

Figure 4: Field plot from a boundary element model, (Lorentz by IES).

However, there is little natural symmetry in an assembly of many individual magnet segments, so the entire design process will count for nothing if there is no empirical validation of the actual device. Typically, a boundary or finite element model will not contain the trappings of a real world device. Features such as glue joints, boltholes and tiny material variances all contribute to the actual field that is achieved. The verification of this field is of the utmost importance, as it allows the engineer to assess the model he created. If the mapped results are more than 5% from the modeled results, that would indicate that either there was a manufacturing problem, or a problem with the model. (A magnetic systems design engineer must ask intelligent questions of himself. The most important of these being, “Does that model result make sense?”). It is not uncommon for modeling software to generate wildly inaccurate solutions due to just one incorrect setting.

The device modeled in Figure 4 was fabricated and them mapped using a 3-axis magnetic field mapper. The results are shown in Figure 5 below.

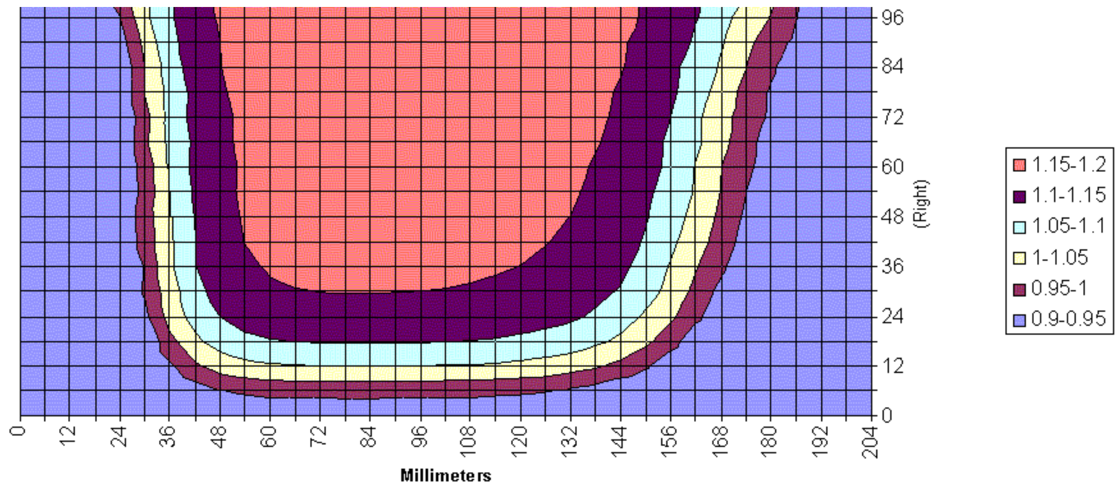

Figure 5: Mapping results for the dipole in Figure 4.

A comparison of the model with mapped results clearly indicates that the device is producing the predicted field. However, it is also noticeable that the mapped field is not quite symmetric. This is not unusual and is merely evidence of the inherent variations of a real world device.

Providing the end user with a magnetic field map guarantees that the expectations of the design have been satisfied. This in itself is a value added service to the end user. However, one must not forget the value of this data to the magnetic design engineer. It would be obvious, for instance, if the device was not performing as it should. If there were un-magnetized, or out of spec magnets, within the assembly, they would manifest themselves as mild to severe perturbations in the mapped field.

Analyzing the results

Depending on the application for which the magnetic system was designed, simple formulae can be used to represent any particular component of the mapped magnetic field. Given that the data will be acquired for the three orthogonal components of field, one can find direction, and magnitude by using the following equations.

$$B_m = \sqrt{B_x^{\,2} + B_y^{\,2} + B_z^{\,2}}$$

Equation 1: Equation to determine the magnitude of the magnetic field.

$$B_{\tan} = \sqrt{B_x^{\,2} + B_y^{\,2}}$$

Equation 2: Equation to determine the in plane, (tangential), component of magnetic field

To make calculations of the direction of the magnetic field, additional factors must be considered. For instance, to calculate the angularity of the magnetic field in the airgap of a dipole, the following steps may be applied:

- Make sure the linear motion of the probe is parallel to the physical device.

In order to do this, the probe is moved parallel to a suitable surface or edge and its distance from the reference edge to the probe at 2 different positions is measured. For accuracy it is advisable to have the non-magnetic support frame of the mapper mounted on sturdy, low friction lockable castors. This will make it easier to adjust the position of the mapper in order to make the probe path and reference edge parallel.

The next step is to rotate the probe about its own axis, in order to position the elements within the probe to read with as little error as possible.

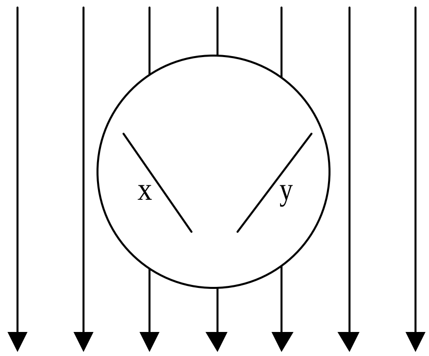

Figure 6: Approximately aligned probe.

With reference to Figure 6, the probe can be approximately aligned parallel to the field. In a dipole, it is usually a safe assumption that the region of most parallel field is at the center of the airgap. However, this may not always be the case and the user must recognize the design intent of the device. The probe can then be rotated about its own axis until the x and y elements see approximately the same field. It is very difficult to do this with a great degree of accuracy. The goal is to insure that readings will be in similar ranges. This reduces the potential for calibration error when one element sees virtually no flux. If the x and y values are within 5-10% of each other, that is acceptable.

However careful you are, it is unlikely you will be able to manually rotate the probe until both x and y elements are reading exactly the same. For this reason there will be a rotational offset between the true axes of the device, (as defined by its geometry), and the measured axes. After placing the probe in the aforementioned region of parallel field, the angular offset (in a system where y is in the direction parallel with the flux across the airgap, and x is the cross field component), can be calculated by Equation 3,

$$q = \tan^{-1}\left(\frac{Bx}{By}\right)$$

Equation 3: Determination of the offset angle between the true axes, (X and Y) and the measured axes, (x and y).

where B_x is the measured x component of the field and B_y is the measured y component of the field*. Once this offset is calculated, the following diagram can be used to calculate the true magnetic vector components in the airgap of the dipole, B_X and B_Y.

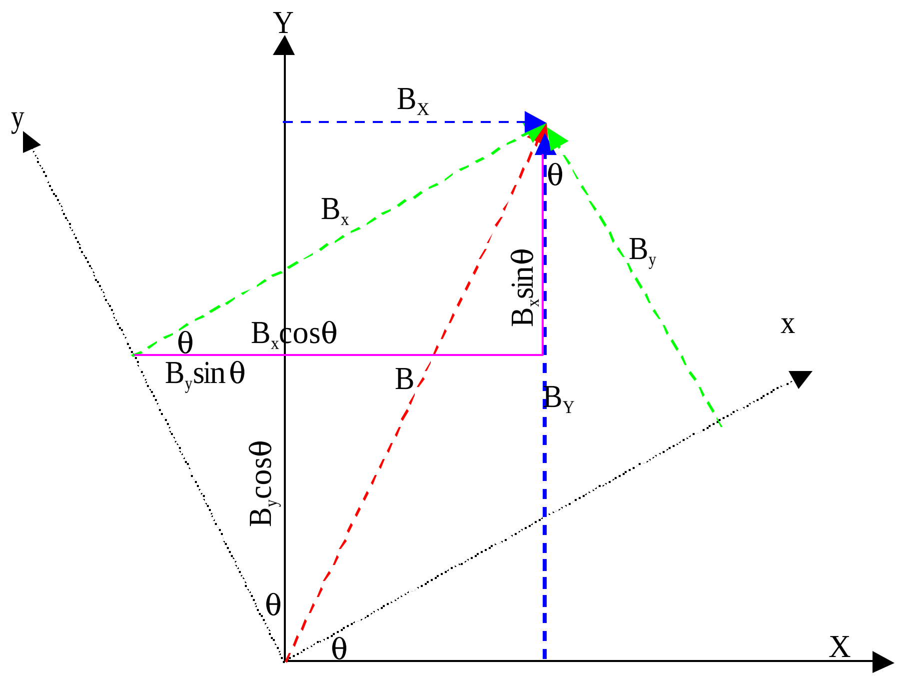

Figure 7: Construction diagram for the deduction of true magnet components.

X and Y represent the true axes, as defined by the geometry of the device itself, x and y represent the measured vectors, offset by an angle θ from the true axes. The red vector

---

* It is assumed in this paper that UPPER CASE letters refer to the true axes, and lower case letter refer to the measured axes.

represents the magnitude of the magnetic vector. The green vectors represent the x and y components of the measured magnetic field. The blue vectors represent the X and Y components of the true magnetic field. The offset angle θ has already been calculated in Equation 3, so all that we need to do is to determine B_X and B_Y in terms of $B_{x,}$ B_y and θ.

From Figure 7, it can be deduced that;

$$B_X = (B_x \cos\theta) - (B_y \sin\theta)$$
$$B_Y = (B_x \sin\theta) + (B_y \cos\theta)$$

Equation 4: True field components as a function of measured field components.

This conversion of measured to true magnetic components can be easily incorporated into any spreadsheet.

The presentation of results is made simple by the use of pivot tables. Typically the data stored by the PC will be a field de-limited text file that can be read into most spreadsheet applications. The data is then transposed automatically by the pivot table function. A surface plot can then be generated. Another useful presentation tip is to allow the field contour plots to be “flipped” through so that individual planes can be viewed on their own, or in the context of the entire mapped volume. Properly presented data can also be part of the value added service to the end user. It will enable them to directly relate observed phenomena, and performance of their device, to the actual magnetic field.

Mapping Magnetizing Coils

Another use for a 3-axis magnetic field mapper is as a troubleshooting tool for magnetizing coils. A common assumption is that, given sufficient field intensity, anisotropic material will magnetize correctly. However, isotropic material, such as the bonded

Neodymium Iron Boron magnets, may manifest concentricity errors between the coil windings and the fixture itself as skewed orientations within the material.

By driving the windings with a nominal steady current that does not cause excessive heating, but such that there is a measurable field within the bore of the fixture, the magnetic field can be mapped. The map can be used to assess whether the magnetizing field of the coil is located concentrically within the structure of the fixture itself and if it produces geometry related artifacts that may be reflected in magnetized part.

Conclusions

This paper has outlined the many benefits of using a 3-axis magnetic field mapper, both to the end user and the magnetic system designer. These benefits include;

- Design validation tool for magnetic systems and assemblies
- Marketing tool, (magnetic field maps, as a product improvement tool, can be part of the value added service to the end user)
- QC tool for system and assembly troubleshooting

Despite the apparent simplicity of the system, there are some potential areas for inaccuracy. These potential errors may be avoided by;

- Ensuring that the elements are aligned optimally to minimize errors.
- Compensating for the position of the Hall elements within the probe
- Compensating for the offset between the measured and the true axes of the device