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Finite Element Model of a Magnet Driven Reed Switch

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Abstract: A simple proximity sensing circuit is made using magnets actuating reed switches; these switches are wired into a larger circuit that performs auxiliary functions. The success or failure of such systems is a function of their position.

The modeling of the system was simplified to modeling just the magnetic portion of the system. The switch interaction was modeled separately based on empirical data. The magnetic model calculated and visualized a magnetic field based on known geometric and magnetic properties. Switches were tested empirically to understand their magnetic characteristics and to perform a correlation between operation specifications and magnetic properties.

The *(x,y)* coordinates along the path of the switch through the magnetic field is calculated as well as the magnetic strength for each point. The operation points of the switch were predicted to a 0.84% error in the *x* direction and 2.87% in the *y* direction for switch closure and to 1.00% in the *x* direction and 1.27% in the *y* direction for switch opening.

Keywords: Proximity sensing, magnetic field, flux density, interpolation.

1. Introduction

1.1 Reed Switches

There were two patents published on the development of the reed switch – 2,187,115 and 2,264,746. A reed switch is comprised of two cantilevered iron/nickel alloy reeds susceptible to magnetic influence placed inside a sealed glass tube filled with inert gas. Under a magnetic field, the reeds are able to carry the magnetic field; as such a “north” and “south” pole are induced on opposite reeds.[1] The air gap between the reeds creates a magnetic potential (analogous to a voltage drop in an electric circuit), closing completely with enough potential, thereby completing the electrical circuit. With no potential, the elastic properties of the reeds return them to their original position.

1.2 Magnets

Maxwell states an electromagnetic field has four vectors associated with it - the **E** (electric field) and **B** (magnetic flux density) vectors, and the **D** (electric flux density) and **H** (magnetic field) vectors; since this study is devoted to the magnetic field, it is the magnetic intensity vector **H** and the magnetic induction vector **B** that will be of the most intimate interest. The **B** and **H** vectors are subject to Maxwell’s equations[2]

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \qquad (1)$$

$$\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J} \qquad (2)$$

In addition, the **B** and **H** vectors are related by a material property known as the permeability coefficient, μ. The physical definition of the permeability of a material is its measure to carry the **B** vector. Further, the relative permeability μ_r can be defined as the quantity μ referenced to the permeability of air, μ_a. The value for μ_a is $4\pi \times 10^{-7}$ H/m. The magnetization **M** in permanent magnets is independent of the applied fields, and therefore the equation relating **B** to **H** changes to[3]

$$\mathbf{B} = \mu(\mathbf{H}+\mathbf{M}) \qquad (3)$$

Magnets are typically specified by a residual induction (B_r), coercive force (H_c), and energy product (BH_{max}). The value of B_r is a measure of the magnet’s maximum flux output, albeit within a completely closed magnetic circuit within the material itself, a situation that has no practical value. Therefore, a magnet’s useful flux is a value lower than B_r.

In most instances, permanent magnets are magnetized to saturation. In order to return the

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[1] Reed Switch Databook, Version 1.00, December 2004. pg 7.

[2] Stratton, p. 1.

[3] Smythe, p. 426.

magnet to a non-magnetic state, i.e. where the **B** vector is zero, a coercive force H_c is required that will demagnetize the magnet until the observed induction B_r is zero. This value is closely related to the intrinsic coercive force H_{ci}, defining the material's ability to resist demagnetization.

2. Application Description and Procedure

The goal of this project was to determine the position of a magnet relative to a reed switch at the instant where the magnet closes the reed switch. The switch is kept in a fixed position while the magnet swings towards and away from the switch on an arc as shown in Figure 1. With a validated finite element model (FEM) to visualize the magnetic field and to determine the strength at any given point, the designer need only know the sensitivity of the reed switch in use, specified in units of Ampere-turns (AT). A test coil with a known relationship between current and magnetic strength can be used to obtain the operation points in Ampere-turns of the switch, and therefore be able to calculate the Gauss strength operating the switch.

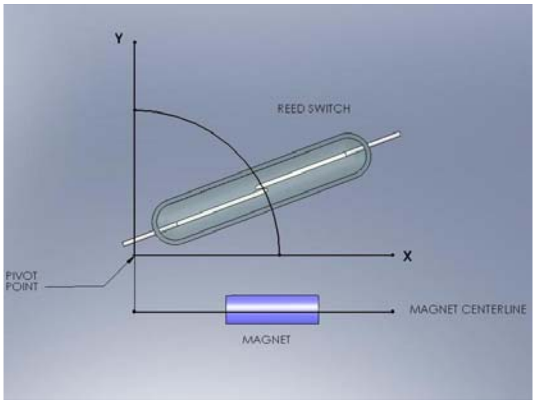

Figure 1. Schematic of Magnet and Reed Switch System.

2.1 Model Creation

Using COMSOL, a 2-D (r-z coordinates) magneto-static analysis was performed using an iron magnet, 0.128” in diameter, 0.400” long with the axial centerline of the magnet used as a boundary of the model, thereby using half the magnet for the model. The far field boundary of the model geometry was a cylinder (rectangle in r-z coordinates) whose material properties were assumed as equal to those of air. Continuity conditions were imposed at the three boundaries (north pole, south pole and side wall) between the magnet and air, while the air boundaries at the outer edge of the model were defined as magnetically insulated. The magnet was modeled as iron, using a magnetization of 1.6×10^5 A/m and a relative permeability of 4000. The model was meshed, solved, and then analyzed. For this analysis, results became mesh insensitive when the number of elements was 15,472 (elements were triangular yielding 7859 nodes). The model was solved as a static problem, using the stationary solver in COMSOL.

For post processing of the model, the r- and z-components of the flux density vector were plotted, as well as the resultant normal vector of the r- and z- direction vectors. These plots were made as contour plots showing a range of flux densities in units of Gauss. The output values for all three plots were exported to a text file for further analysis using Microsoft Excel.

2.2 Model Validation

To validate the model, a precise XY measurement station was used with a magnet mounted to it. A gauss probe was mounted in a fixed location allowing the magnet to move relative to the probe. The probe is pointed parallel to the axial centerline of the magnet, analogous to the z-direction vector output. The probe was placed 3.9 mm from the centerline of the magnet and moved along the length of the magnet. Gauss measurements were taken along this line at intervals of 0.3 mm and plotted with position on the abscissa and Gauss on the ordinate. A cross-sectional plot was generated in COMSOL to match the same measuring path as the empirical test and then plotted with the empirical data. This data can also be taken from matching a specific row of data points corresponding to the test points within the magnetic field in the Excel data.

2.3 Procedure

Using an actual magnet/ reed switch system, the position of the switch is measured relative to the pivot point, as is the magnet centerline. The switch will move on an arc through the magnetic field while the magnet remains stationary. The switch was articulated towards the magnet until the switch closed, and the location of the switch was measured again in reference to the pivot. The switch was then articulated away from the magnet, causing it to open. Again, the position of the switch was carefully measured. All measurements were in the form of (*x*,*y*). Since the switch location is known, the radius of the arc is defined, and the (*x*,*y*) coordinates can be calculated for any point along the arc. In Excel, these points were calculated based on an *x*-coordinate resolution of 0.02 mm. The exported data from COMSOL was used as a lookup table to interpolate a value of magnetic strength in Gauss for each data point on the arc and was tabulated as another lookup table.

Values for both the pull-in and dropout (the switch operation points) of the switch in Ampere-turns (AT) were inserted into the correlation equation empirically calculated to obtain values of Gauss for these points. A second interpolation was made from the lookup table created for the Gauss values along the switch arc to find the location along the arc that corresponded to the Gauss value that operates the switch.

3. Results

3.1 Reed Switch

To properly test the reed switch, a manufacturer-specified test coil was acquired and used for the analysis. Reed switches are specified in terms of ampere-turns (AT). It is well known from basic electromagnetic theory that a coil of wire can create a magnetic field when current is passed through it; hence an effective way to specify the sensitivity of a reed switch is to use a formula for calculating AT

$$\mathrm{AT} = \mathrm{I}\, n \qquad (4)$$

where I is current and *n* is the number of turns in the coil.

The test coil used contained 5000 turns of wire. The switch used for this project was placed inside the coil, and the voltage on the power supply increased, thereby increasing the current in the coil, and thus the magnetic field. The current for the switch closing was 5.827 mA, while the current for the switch opening was 3.746 mA.

3.2 Gauss to Ampere-Turn Correlation

The gauss probe was placed within the test coil such that the element of the probe was centered in the coil. The power supply was adjusted for a given value of current in the coil as monitored by the ammeter, allowing the curve to be created with different values of current and their corresponding Gauss measurement. Using a least-squares curve fit to the data, an equation that will correlate a value of ampere-turns to gauss is

$$G = 0.5406\, AT - 1.1807 \qquad (5)$$

where *G* is gauss. It should be noted that this graph does not include the data point (0,0) corresponding to the case when no current, and therefore no magnetic field, is present within the coil. Inclusion of this data point changes this equation of best-fit to

$$G = 0.5328\, AT - 0.8565 \qquad (6)$$

Using Equation 4, the pull-in and dropout of the switch in gauss occurred at 14.570 G and 8.945 G, while Equation 5 yields values of 14.667 G and 9.123 G.

3.2 Model Verification

As mentioned in Section 2.2, a magnet was placed onto a precise XY measurement table with a gauss probe placed 3.9 mm away and parallel with the magnet centerline. While keeping the gauss probe stationary, the float was moved in increments of 0.3 mm (equal to the resolution of the Excel data exported from COMSOL) and a gauss measurement was taken. This data was plotted in a chart along with the row of exported data corresponding to 3.9 mm in the z-direction COMSOL model in absolute values. The results of this can be seen in Figure 2.

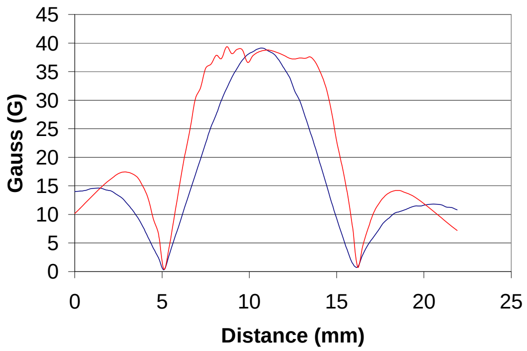

Figure 2. Gauss Plot, Empirical vs. Model. Red = Model, Blue = Empirical.

3.4 Further Analysis of COMSOL Results

Additional post processing of the model results yielded the magnetic flux density in the r-direction, z-direction, and normal direction. Plots of the normal direction and z- direction output can be found in Figure 3 and Figure 4.

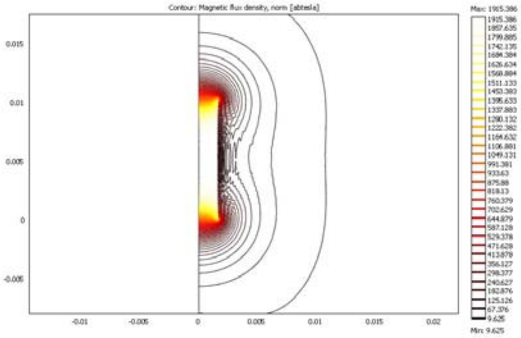

Figure 3. Normal Direction.

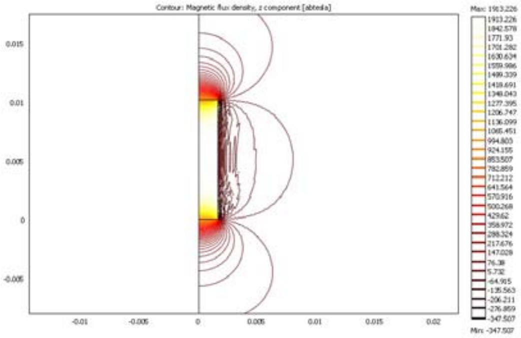

Figure 4. *r*-direction.

The normal plot, or resultant field of the *r*- and *z*-direction vector, was used considering that the switch will move on an arc through the field. The magnetic flux density was exported to Excel as a series of (x,y) coordinates with a resolution of 0.3 mm in each direction. As mentioned in Section 2.3, the switch location is 15.63 mm from the pivot point, defining the radius of the switch arc. Points on this arc are easily calculated such that their coordinates can be interpolated within the (x,y) coordinate table. This will yield a value for flux density for each point on the arc.

3.5 Matching Switch Data to Model

Equations (5) and (6) allow for a correlation between the switch sensitivity in Ampere-turns (AT) and Gauss. With the operating points of the switch known in Gauss, a second interpolation can be done using the points defined by the switch arc. As mentioned, a switch that closes at 29 AT converts to 14.57 G, a value that occurs on the switch arc to (15.47, 8.72) mm. A switch opening at 18.7 AT converts to 8.95 G occurring at (14.98, 10.96) mm. When an actual magnet/switch system was measured as in Section 2.3, the closing point was (15.34, 8.97) mm and the opening point was (14.83, 10.82) mm. Table 1 shows the results in tabulated form.

	x, closed	*y*, closed	*x*, open	*y*, open
Model	15.47	8.72	14.98	10.96
Observed	15.34	8.97	14.83	10.82
Error	0.84%	-2.87%	1.00%	1.27%

Table 1. Switch operation location, model vs. empirical.

4. Conclusions

The finite element model generated by COMSOL has done particularly well in predicting the correct operating locations of a reed switch within a magnetic field, calculating the operating points to approximately 2%. With that said, there are a few items that should be noted to supplement this analysis.

From Table 1, there is more error in the *y*-direction than the *x*-direction. On a circle, the rate of change in *y* versus a constant value of *x* for any change in position from (x,y) to (x_1, y_1) is greater as $sin(\theta)$ approaches zero and $cos(\theta)$ approaches zero. Therefore, as the angle between the magnet centerline and the switch centerline decreases, the error in the *y*-direction increases as the slope of the curve approaches infinity.

Second, the maximum angle at which the magnet can travel in the application is approximately 20^o from horizontal. The magnet should operate the switch around 10^o such that temperature changes will not affect the switch point, adding a factor of safety in the case of magnetic drift. It is known that increasing temperature weakens a magnetic field, and large increases in temperature have an effect on the hysteresis curve. In this application, two different sensitivity ranges of switches are used; this analysis uses the higher range. Here, the switch does close at 9.96° of arc, however opens at 18.34°. This range of movement is on the limits of acceptability. Further, an observation of Figure 3 shows that if the Gauss sensitivity of the switch decreases, the switch will remain closed over the entire span of float travel.

Third, this model is a simplification of the actual system. Any time a material with magnetic susceptibility is placed within a magnetic field, the magnetic field will be altered. Further work must be done to model the effects of this. Due to the percentage of additional magnetic material within the field from the switch leads, an estimated 5% deviation in results might be expected.

5. References

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