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Optimal design of fine magnetic pole pitch fabricated on printed circuit board

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Using traditional methods, a permanent magnet multipole component magnetized with a magnetic pole pitch of less than 1 mm is very difficult to achieve and a costly, complicated magnetization system is required. In this paper, the optimal design of a fine magnetic pole pitch of less than 1 mm fabricated on a printed circuit board has been successfully investigated and demonstrated. An optimal magnetic pole pitch having large variation and strength in magnetic-flux density was obtained. The characteristics of the optimal magnetic pole pitch are good for signal detection and processing. The measured values of the magnetic-flux density in the z component are in agreement with the calculated values. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1851430]

INTRODUCTION

Magnetic encoders are widely used in detecting the rotation speed, angle, and position in many precise control systems. It consists of a magnetic reading device and a multipole magnetic component with a fine magnetic pole pitch. Using traditional methods, a permanent magnet multipole component magnetized with a magnetic pole pitch of less than 1 mm is very difficult to achieve and a costly, complicated magnetization system is required.[1–5] In this paper, printed circuit board (PCB) technology was employed to fabricate a component with a fine magnetic pole pitch of less than 1 mm having a uniform pole structure, as shown in Fig. 1. After supplying a steady current through the wire circuit from point A to point B, an alternative and regular magnetic-field distribution is induced according to Ampere's law. Thus, a multipole magnetic component with a fine magnetic pole pitch of less than 1 mm was formed. The summation of wire width $T1$ and gap is defined as the magnetic pole pitch. An optimal design of a fine magnetic pole pitch fabricated on PCB having large variation and strength in magnetic-flux density is discussed. Both the experimental measurement and theoretical computation for different magnetic pole pitches are investigated.

THEORETICAL ANALYSIS

According to the Biot–Savart law,[6] for a finite length L, straight wire carrying a steady current I, as shown in Fig. 2(a), the magnetic-flux density at point P with a distance r is given by

$$B = \frac{\mu_0 I}{4\pi r}\left(\frac{a}{\sqrt{a^2+r^2}} + \frac{b}{\sqrt{b^2+r^2}}\right)\hat{\phi}, \tag{1}$$

where μ_0 is the permeability of free space and $\hat{\phi}$ is the unit vector in cylindrial coordinates.

In fact, the cross section of a circuit wire on PCB is not circular but rectangular which can be discretized into a mesh of indexed elements, as shown in Fig. 2(b). These elements are equal in area containing the same amount of current density. Both wire width $T1$ and wire thickness $T2$ should be considered when $T1 \approx r$ and $T2 \approx r$. Each small element is a finite length and straight wire and therefore the magnetic-flux density can be calculated by Eq. (1). After summing the contribution of each element, the total magnetic-flux density in the z component is given by

$$Bz = \sum_{n1=1}^{m1}\sum_{n2=1}^{m2} \frac{\mu_0 i}{4\pi R_{n1,n2}}\left(\frac{a}{\sqrt{a^2+R_{n1,n2}^2}} + \frac{b}{\sqrt{b^2+R_{n1,n2}^2}}\right)\sin\theta, \tag{2}$$

where $n1$ and $n2$ are integers, $m1$ and $m2$ are the number of elements as "mesh" parameters that characterize the discretization of the cross section of a wire, and θ is the angular

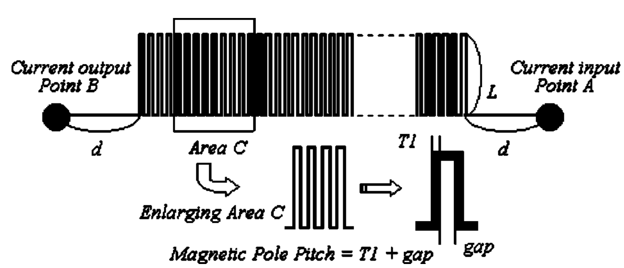

FIG. 1. Special wire circuit fabricated on PCB.

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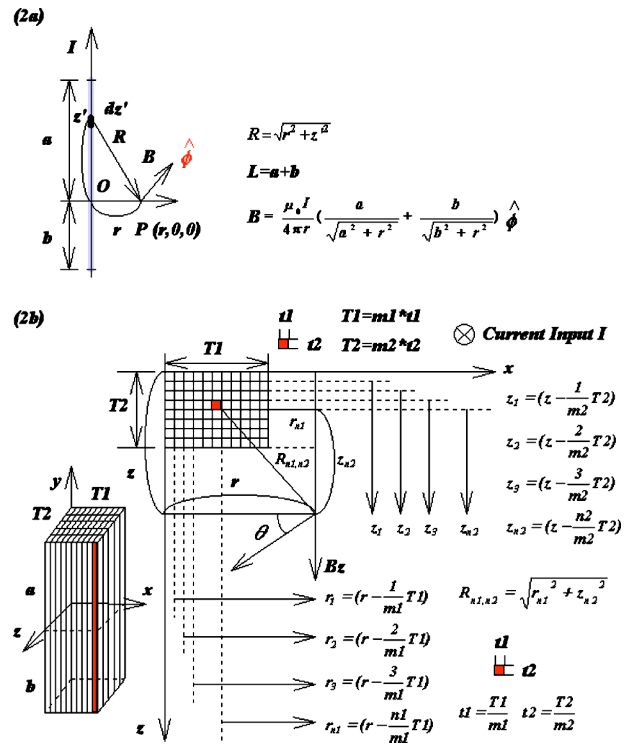

FIG. 2. Mesh of cross section on the circuit wire.

offset of the x axis. The parameters of i, $R_{n1,n2}$, and $\sin\theta$ are given by

$$i=\frac{I}{m1m2},\quad R_{n1,n2}=\sqrt{r_{n1}^2+z_{n2}^2},\quad \sin\theta=\frac{r_{n1}}{R_{n1,n2}},\tag{3}$$

$$r_{n1}=\left(r-\frac{n1}{m1}T1\right),\quad z_{n2}=\left(z-\frac{n2}{m2}T2\right),$$

$$(n1=1\sim m1,n2=1\sim m2).\tag{4}$$

The wire circuit fabricated on PCB can be treated as many finite and straight wires that are located at different positions. The magnetic-flux density in the z component for each wire can be calculated by Eq. (2). Consequently, the total magnetic-flux density in the z component at any position can be obtained after accumulating the contribution from each wire part on PCB.

RESULTS AND DISCUSSIONS

Supplying a 1-A current into a straight wire with a length L of 6 mm and a thickness $T2$ of 41 μm, the different magnetic-flux density distributions in the z component on the bisection position $(a=b=L/2)$ were calculated at a detection spacing of 200 μm above the surface by using Eq. (2). Wire width $T1$ was designed at values of 190, 235, and 280 μm, respectively. The steep slopes and positions of the maximum magnetic-flux density in the z component were found as shown in Fig. 3. The large variation and strength in magnetic-flux density appeared at a distance smaller than the position of the maximum magnetic-flux density. These characteristics are good for signal detection and processing. Since each straight wire fabricated on PCB in Fig. 1 is symmetric, the gap between two adjacent straight wires was designed at twice the value of the difference between wire width $T1$ and the position of the maximum magnetic-flux density. As a result, the optimal magnetic pole pitches on different wire widths $T1$ were obtained. Table I shows the different wire widths $T1$, positions of maximum Bz, gaps, and optimal magnetic pole pitches, respectively.

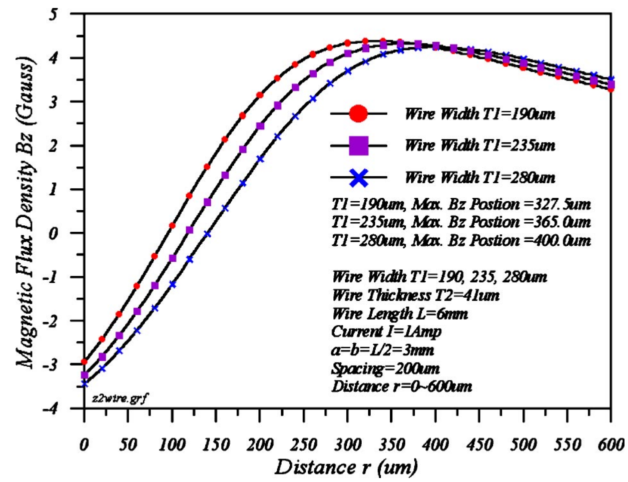

FIG. 3. Calculated magnetic-flux density as a function of distance r at a detection spacing of 200 μm.

Nine-pole magnetic components were fabricated on PCB with different wire widths $T1$ and gaps to make different fine magnetic pole pitches. Three central consecutive magnetic poles of the magnetic-flux density distributions in the z component at a magnetic pole pitch of 465 μm were measured on the central line by using a precise Hall probe, as shown in Fig. 4. The sensing area of the Hall sensor inside the precise Hall probe is only $165\times165\ \mu m^2$ and therefore it is capable of measuring the fields of the fine magnetic pole pitch fabricated on PCB. The measured data at any point is the average value over the sensing area of the Hall sensor in measurement. The circle and square marks denote the magnetic-flux density distributions at the detection spacing S of 200 and 300 μm, respectively. The detection spacing S is the distance of the Hall sensor from the surface of the multipole wire array on PCB. The variation of the magnetic-flux density in the z component was decreased significantly as detection spacing increased and obviously indicated that a fine magnetic pole pitch of less than 1 mm was feasible.

Using a wire width $T1$ of 190 μm, the magnetic-flux density distributions in the z component on the central pole were measured at a detection spacing S of 200 μm above the surface of the multipole wire array with different fine magnetic pole pitches of 365, 465, and 565 μm, as shown in

TABLE I. Different wire width $T1$, position of maximum Bz, gap, and optimal magnetic pole pitch.

$T1$ (μm)	Position of max. Bz (μm)	Gap (μm)	Optimal magnetic pole pitch (μm)
190.0	327.5	275	465.0
235.0	365.0	260	495.0
280.0	400.0	240	520.0

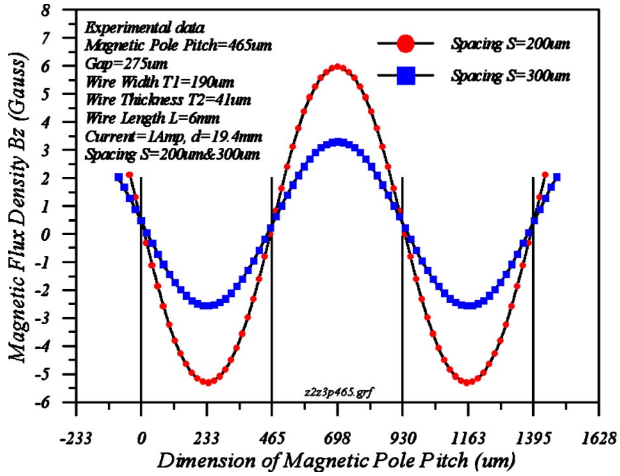

FIG. 4. Magnetic-flux density distributions measured at a magnetic pole pitch of 465 μm.

Fig. 5. Clearly, the optimal magnetic pole pitch at the value of 465 μm has larger variation and strength in magnetic-flux density than the others. Although the magnetic-flux density at the pitch size of 565 μm is a little bigger than that of 465 μm, the variation of the magnetic-flux density is smooth between line A and line B, and the large pitch size will decrease the resolution in applications. In addition, the measured values of the magnetic-flux density in the z component are in agreement with the calculated values. Figure 6 shows the magnetic-flux density distributions in the z component on the central pole measured at a detection spacing S of 200 μm above the surface of the multipole wire array with different fine magnetic pole pitches of 395, 495, and 595 μm using a

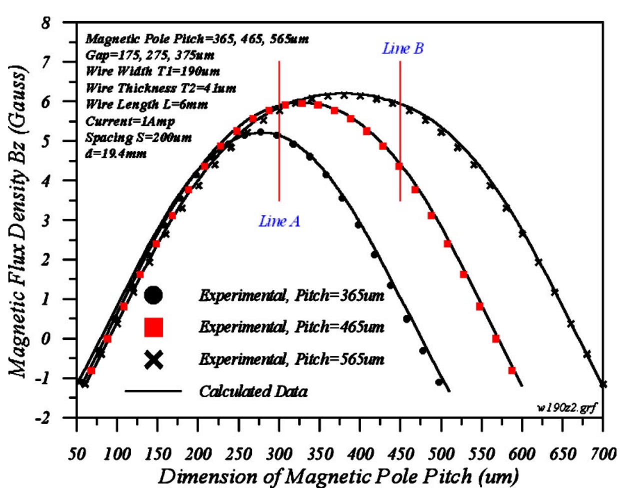

FIG. 5. Experimental and calculated magnetic-flux density distributions on the central pole at a wire width $T1$ of 190 μm.

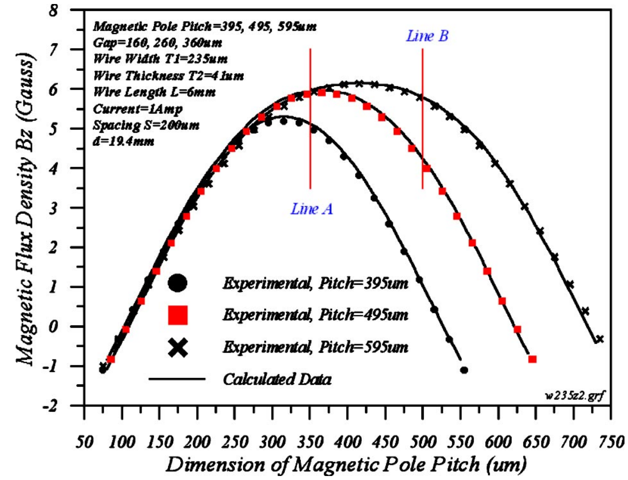

FIG. 6. Experimental and calculated magnetic-flux density distributions on the central pole at a wire width $T1$ of 235 μm.

wire width $T1$ of 235 μm. The same smooth variation in magnetic-flux density at the pitch size of 595 μm was found between line A and line B like in Fig. 5. The optimal magnetic pole pitch at the value of 495 μm holds the larger variation and strength in magnetic-flux density than the others.

CONCLUSIONS

The optimal design of a fine magnetic pole pitch of less than 1 mm fabricated on PCB has been successfully investigated and demonstrated. An optimal magnetic pole pitch having large variation and strength in magnetic-flux density was obtained. The characteristics of the optimal magnetic pole pitch are good for signal detection and processing. The measured values of magnetic-flux density in the z component are in agreement with the calculated values. Additionally, PCB technology provides a simple way to fabricate the fine magnetic pole pitch of less than 1 mm without the costly complicated magnetization system and precise mechanical processing. Different dimensions of magnetic pole pitches can be achieved easily by modifying an appropriate wire circuit pattern on PCB.

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