2D Hall Sensor Array for Measuring the Position of a Magnet Matrix

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Hall sensor array is used to measure the position of a magnet array and needs compensation of errors caused by manufacturing tolerances as well as harmonic components of the magnetic flux of the magnet array. This paper presents a 2D hall sensor array to measure the position of a magnet matrix by filtering harmonic components. First, 1D sensor array to filter out arbitrary number of harmonic signals is proposed and extended to 2D sensor array for the position measurement of a magnet matrix. A 2D hall sensor array for filtering both fundamental and 2nd harmonic components of the magnetic flux and its conditioning circuit board are built to measure the position of the magnet matrix for a planar motor. Finally, performances of filtering harmonics and measuring position of the magnet matrix are experimentally verified with a XY linear motion stage. The proposed 2D hall sensor array is compatible to a sine encoder and is directly applicable to commercial motion controllers.

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NOMENCLATURE

A = Sensor gain

f = Sensor output

L_i = i^{th} Sensor location

W_n = Total width of sensor array of n sensors

x = Physical quantity (displacement)

α = Phase angle of harmonic component

λ = Wavelength of harmonic component

1. Introduction

Manufacturing equipment usually needs precise multi-degree of freedom (DOF) motions as well as compact, lightweight and high-stiff structures. For the multi-DOF motion stage, conventional stacked, gantry and hybrid structures have been used so far. However, these conventional structures are reaching the limit to satisfy pressing demands for fast-response and high-precision motion.¹

Planar motors have been studied in several research groups to meet the high-speed, precise, compact and lightweight needs for the multi-

DOF motion stage.²⁻⁹ Although there are several types such as moving coil type⁴ and reluctant motor,¹⁰ planar motors with moving magnet matrix were mostly studied.^{2,3,5-9}

There are several sensing options for planar motors such as interferometry,^{2,5} capacitance gauge,² encoder,^{11,12} hall sensors^{13,14} and vision sensor.¹⁵ Using hall sensors is most cost-effective methodology since the magnet matrix is used as the measured target and various hall sensors are available at low cost. However, magnetic flux density distribution of the magnet matrix does not have perfect sinusoidal wave due to harmonics and manufacturing tolerance. Therefore, error separation technique is required to improve the accuracy.¹⁴ In addition, the hall sensors need customized interface rather than standard interface of general motion controller.

Harmonic components of magnetic flux distribution of the magnet matrix can hardly be removed using conventional filter techniques since frequencies of harmonic components vary according to the motion speed of the mover. Halbach magnet array can significantly reduce harmonic components of magnetic flux density.^{14,16} In addition, periodic (harmonic) signals can be separated using multi-sensors (or sensor array).¹⁷⁻¹⁹ If the harmonic components are removed, we can save considerable efforts on error compensation and improve intrinsic accuracy of the sensing system.

In this paper, we propose a 2D hall sensor array to measure the position of a magnet matrix by filtering harmonic components of magnetic flux of the magnet matrix. First, 1D sensor array to filter out arbitrary number of harmonic signals is proposed and extended to a 2D sensor array for position measurement of a magnet matrix. A 2D hall sensor array and its conditioning circuit are built to measure the position of the magnet matrix for a planar motor. The 2D hall sensor array is directly applicable to commercial motion controller because of its compatibility to a typical sine encoder. Finally, the harmonic filtering performance of the 2D hall sensor array is experimentally verified with a XY linear motion stage.

2. Sensor Array for Filtering of Harmonic Signals

2.1 1D Sensor Array

At least, two sensors (s_1 and s_2) are required to remove a harmonic component of wave length λ_1 . Two sensors should be separated in half wavelength (or π phase difference) of the harmonic component.¹⁴ That is, a sensor has output of $f(x\lambda_1/4)$ and the other sensor has output of $f(x+\lambda_1/4)$, where x is a dependent variable for a physical quantity (displacement). If the sensor output f is a pure harmonic function of $A_1\sin(2\pi x/\lambda_1)$, sum of two sensor outputs always becomes zero, as shown in Eq. (1) and Fig. 1(a).

$$A_1\sin(\pi x/\lambda_1 - \pi/2) + A_1\sin(\pi x/\lambda_1 + (\pi/2)) = 0 \quad (1)$$

If we want to remove another harmonic component of wavelength λ_2 at the same time, we have to divide one sensor (s_1 or s_2) into two sensors (s'_1 and s'_2 or s'_3 and s'_4). In addition, the locations of the sensors should be separated in half wavelength of λ_2 as shown in Fig. 1(b). Then, four sensor outputs should be $f(x\lambda_1/4\lambda_2/4)$, $f(x\lambda_1/4 + \lambda_2/4)$, $f(x + \lambda_1/4\lambda_2/4)$ and $f(x + \lambda_1/4 + \lambda_2/4)$. The sensor output contains two harmonic components such as $A_1\sin(2\pi x/\lambda_1 + \alpha_1) + A_1\sin(2\pi x/\lambda_1 + \alpha_2)$, where α_1 and α_2 are phase angles. We can easily see the sum of all sensors becomes zero.

Fig. 1 Extension of sensor array

Fig. 2 1D sensor array for filtering out n harmonic components

Now, we can extend and generalize this fact to a sensor array for filtering n harmonic components ($\lambda_1 > \lambda_2 > \dots > \lambda_n$). At least, properly located 2^n sensors are necessary to filter out n harmonic components. If the origin is the center of the sensor array, location of the i^{th} sensor, L_i can be expressed mathematically as Eq. (2). Here, $(i-1)2^{n-k}$ is the quotient of division of 2^{n-k} by $i-1$.

$$L_i = \sum_{k=1}^n (-1)^{(i-1)2^{n-k}} \frac{\lambda_k}{4}, \quad i=1, 2 \dots 2^n \quad (2)$$

The sensor location is graphically described in Fig. 2. The first row denotes a sensor array to filter a harmonic component of wavelength λ_1 . The second row denotes a sensor array to filter out two harmonic components of wavelength λ_1 and λ_2 . Finally, we can generalize a sensor array to filter out n harmonic components from wavelength λ_1 to λ_n shown in the last row of Fig. 2.

The total width W_n of the sensor array to filter out n harmonic components is the sum of all half wavelengths of n harmonic components, as shown in Eq. (3).

$$W_n = \sum_{k=1}^n \frac{\lambda_k}{2} \quad (3)$$

Two rows of 1D sensor array are required to identify the direction of the signal since the direction or the phase of the signal is important in some applications such as displacement sensor or encoder. Each row of 1D sensor array is separated each other in one fourth of wavelength of a desired harmonic component, which generates sine and cosine waves. In addition, these sine and cosine outputs are compatible to typical sine encoder for general motion controller. In addition, the height of the magnet matrix from the hall sensor array can be estimated from the magnitude of the magnetic flux density, which is calculated from root mean square of sine and cosine outputs of the hall sensor array.

2.2 2D Sensor Array

1D sensor array can easily be extended into 2D sensor array for multi-dimensional measurement of a magnet matrix. Many combinations such as L and cross shapes are possible as shown in Fig. 3. In addition, m^2 sensors can be saved if m rows of 1D array are used to filter out 1D harmonic component. We can reduce 4 (2^2) sensors if we use one of sensor configurations in Fig. 3.

3. 2D Sensor Array for Measuring Position of the Magnet Matrix for a Planar Motor

3.1 A Planar Motor System with Iron Core

Schematic and photo of a planar motor system are shown in Fig. 4.

Fig. 3 Various combinations of 1D sensor array

The planar motor system consists of a mover with 2D magnet matrix, iron core array, a glass plate, air bearing pads, and a control system including sensors, amplifiers and motion controller. The specifications

Fig. 4 A planar motor system

Fig. 5 Mover with 2D magnet matrix²⁰

Table 1 Specifications of the planar motor

Item	Specifications
Stroke ($X \times Y \times \theta_z$)	160 mm $\times$ 160 mm $\pm 5^\circ$
Maximum thrust force	200 N
Capable load of air bearing	475 N/unit
Mass of mover	6.6 Kg

Fig. 6 Magnetic flux density of 2D magnet matrix

of the planar motor system are described in Table 1. The magnet matrix for the planar motor is not a Halbach array as shown in Fig. 5. Magnetic flux density distribution of the magnet matrix is calculated and shown in Fig. 6. The magnetic flux density is 2D sinusoidal and has various harmonics.

3.2 2D Hall Sensor Array for Measuring Displacement of the Magnet Matrix

A 2D hall sensor array is designed both to decouple 2D sinusoidal magnetic flux density and to filter out harmonic components. Fundamental component should be removed to decouple the 2D magnetic flux density. In addition, most dominant second harmonic component is filtered simultaneously to reduce harmonic distortions.

2D hall sensor array with L shape is built to filter out first and second harmonic components, as shown in Fig. 7(a). 1D sensor array consists of 4 hall sensors that are separated in $1/8$ wavelength and filters out fundamental and second harmonics of the magnetic flux density. The first and second rows of the sensor array filter out fundamental and second harmonic of X directional magnetic flux density while they generate sine and cosine of Y directional magnetic flux density. In the same manner, column array filters out Y directional magnetic flux density and generates X directional magnetic flux density.

A conditioning board for hall sensor array of Fig. 7(a) is shown in Fig. 7(b). The conditioning board consists of several stages of OP-amplifier circuits such as summation of hall sensor outputs and adjustment of gain and offset. The conditioned outputs of the 2D hall sensor array is fed into a motion controller and the motion controller calculates X and Y directional displacements using arctangent function.^{21,22} The motion controller adjusts offset and then converts a relative position from arctangent function into the global position.

3.3 Experiments

Filtering performances of the 2D hall sensor array is experimentally verified using a XY linear motion stage in Fig. 8. The magnet matrix

Fig. 7 2D hall sensor array and its conditioning board

Fig. 8 Experimental set-up for the hall sensor array

is put on the base of the stage and the 2D hall sensor array is mounted on a manual Z stage that is attached to the mover head of the XY stage, as shown in Fig. 8(b). Then, conditioned signals are gathered at various heights and XY positions of the stage.

As the hall sensor array is mounted at 1, 3, 5 and 8 mm height from the 2D magnet matrix, magnetic flux densities are measured and shown in Fig. 9. Fundamental and second harmonic components of magnetic flux density are filtered out. The conditioned output of the hall sensor array is saturated in case of 1 mm height and fourth harmonic component appears from 1 mm to 5 mm heights. As the result, almost pure sine wave magnetic flux density can be obtained at 8 mm height. If we want to measure the magnetic flux density at closer to the magnet matrix than 8 mm, we need 1D array with 8 hall sensors to filter out fourth harmonic components. Magnitudes of harmonic components become strong as the 2D hall sensor array approaches the magnet matrix. The fourth harmonic components of magnetic flux can clearly be seen in Fig. 9(a) and (b), which cannot be filtered out with the 2D hall sensor array.

The four conditioned outputs of the hall at 8 mm height are shown in Fig. 10. The conditioning circuit generates sine and cosine signals of both X and Y directions from the 2D hall sensor array. There are small

Fig. 9 Sensor output of the hall sensor array at various heights

Fig. 10 Sine and cosine outputs of conditioning circuit

wave in magnitude of sine and cosine outputs, which are fundamental component of magnetic flux coming from the manufacturing tolerances and magnet or hall sensor irregularities.

X and Y displacements of the 2D magnet matrix are calculated and the displacement errors are evaluated in Fig. 11. Displacement is obtained using the phase angle from arctangent of the sine and cosine outputs of the conditioning board.^{21,22} The maximum error is about 1 mm and is too large to be acceptable. The errors consist of not only fundamental component of magnetic flux (magnet pitch), but also its multiples (small peaks between fundamental components). In particular, the fundamental component is intrinsic error caused by manufacturing tolerances and irregularity of hall sensors and magnets. These errors can be compensated with an error mapping technique.¹⁴

The magnitude of each directional magnetic flux density is calculated and shown in Fig. 12(a) and (b). The magnitude of each directional flux density can be calculated using root mean square of sine and cosine outputs of conditioning circuit. Although the magnitude of each directional magnetic flux density is flat surface in ideal case, their magnitudes are not constant due to the manufacturing tolerances and harmonic components of the magnetic flux. In addition, average of each directional magnetic flux density is calculated and shown in Fig. 12(c), which can be used to estimate the height of the magnet matrix since magnitude of the magnetic flux density depends on the height of the magnet matrix. The average magnetic flux density looks like rectangular magnet matrix and reveals that there are still considerable harmonic components, which can be reduced by using Halbach magnet matrix or more hall sensors.

Fig. 11 Calculated displacement errors of the hall sensor array

Fig. 12 Magnitude of directional magnetic flux density

4. Conclusions

This paper presents a 2D hall sensor array to measure the position of a magnet matrix by filtering harmonic components of magnetic flux of the magnet matrix. A 1D sensor array is proposed to filter out arbitrary number of harmonic signals. Properly-located 2ⁿ sensors are required to filter out n harmonic components. In addition, the 1D sensor array is easily extended to a 2D sensor array. A 2D hall sensor array and its conditioning board are built to measure the position of the magnet matrix for a planar motor. The performance of the 2D hall sensor array is experimentally verified with a XY linear motor stage.

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