A new high sensitivity magnetic system for microposition measurement

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This article presents a new design of a magnetic system which can be used as a position sensing system for precision measurements. The proposed system consists of driving coils, position-detecting coils, movable cores, and magnetic blocks. The cores are put into the position-detecting coils to draw the flux. As the cores move in a motion proportional to the input position, induced voltages arise in the position-detecting coils. The turns ratio and the air-gap dimensions between the magnetic blocks and the movable cores are selected in such a way as to have high sensitivity. To decrease the flux loss and produce the strong flux density, a symmetric and closed loop form is adopted. The elements that affect the system characteristics and sensitivity are turns ratio, air-gap dimension, capacitance effect, excitation frequency, and so forth. The sensitivity of the newly designed system is greater than 2000 mV/(V mm) and the linearity error is below ±0.10% in the range of ±200 μm. The repeatability standard deviation in this system is below 50 nm. © 2001 American Institute of Physics. [DOI: 10.1063/1.1386901]

I. INTRODUCTION

Sensors based on the magnetic flux are widely used in position detection. Magnetic sensors have been the topic of previous works. These sensors have good linearity over a wide range, high reliability, sufficient durability, and low production costs. The above mentioned magnetic devices are used when a larger position displacement of up to several tens of millimeters is to be detected. The characteristics and advantages are related to the large range.

As the precision and semiconductor industries are rapidly developing, system integration is more complex and the required minimum size is decreasing. In the inspection and measurement process, the required precision and resolution are at the submicron level over the range of several hundred micrometers.

In sensors based on the magnetic flux, the resolution—the smallest measurable input change—is defined as follows:

\[ \text{Resolution} = \frac{\text{Noise}}{\text{Sensitivity}}. \]

The resolution is related to noise and sensitivity. The sensitivity is defined as below. High sensitivity means that the system output is large for the reference position and source amplitude

\[ \text{Sensitivity} = \frac{\text{Output}}{\text{Source-Position}} \left( \frac{mV}{V \cdot \text{mm}} \right). \]

In order to improve the resolution, system sensitivity must be improved or noise must be decreased. Noise level varies with external conditions and is not a fixed value. To be advantageous for detection of small position variations, the system should have high sensitivity and linearity.

In this study, a new magnetic position sensing device for the precision and semiconductor industries is introduced. We are interested in the detection at submicron levels. The device is designed to have high sensitivity and high resolution for the micron region. The experiments are focused on finding the characteristics of the device in this region. This system can be used for the sensing part of devices such as surface measurement systems of various kinds.

II. PRINCIPLE

The principles of our new magnetic based sensing system are explained by Faraday’s and Lenz’s laws. The fundamental postulate for electromagnetic induction is shown below:

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \]

where \( \mathbf{E} \) denotes electric field intensity, and \( \mathbf{B} \) denotes magnetic flux density. Taking the surface integral of both sides of Eq. (1) over an open surface and applying Stokes’s theorem, we obtain

\[ \oint_C \mathbf{E} \cdot d\mathbf{l} = -\oint_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{s}. \]

For a stationary circuit with a contour \( C \) and surface \( S \), Eq. (2) can be written as

\[ \oint_C \mathbf{E} \cdot d\mathbf{l} - \frac{d}{dt} \oint_S \mathbf{B} \cdot d\mathbf{s}. \]

If we define \( \nu = \oint_C \mathbf{E} \cdot d\mathbf{l} \) and \( \phi = \oint_S \mathbf{B} \cdot d\mathbf{s} \) then Eq. (3) becomes

\[ \nu = -\frac{d\phi}{dt}. \]
From Eq. (4), we know that the induced output voltage is proportional to the time derivative of the flux. We designed a system in which the flux is varied proportionally to the input position.

Figure 1 shows the schematic design of the proposed system. The dimensions of the prototype are shown in Fig. 2. It consists of driving coils, position-detecting coils, movable cores, and magnetic closed loop formed blocks. Mn–Zn ferrite is used for the cores and the magnetic blocks. When the driving coil is excited with a sinusoidal ac voltage, a magnetic field is generated within the system. Figure 3 shows the simulation result of the flux distribution, where (a) is the finite element mesh used in the Maxwell equation simulation package and (b) is the flux density plot. Figure 4 shows the simplified flux path at the center position based on the simulation result. The simulation result using the Maxwell simulation package shows that the flux path is generated along the magnetic closed loop formed blocks and thus the flux loss is reduced. The magnetic core is put inside the position-detecting coil to draw the flux. To generate a strong flux, only narrow gaps between the magnetic blocks and the movable cores are allowed. This design attempts to produce a large flux difference even for a small position variation. It is customary that the two position-detecting coils are connected to produce a differential output to reduce the noise. In the center or null position, each output voltage is equal; therefore, the differential output voltage is zero. When the inner cores move together proportionally to the input position, the magnetic flux of each core is changed. As the cores are moved downward, the flux $\phi_I$ is increased and the flux $\phi_{II}$ is decreased as shown in Fig. 5. This flux difference between the two cores generates a differential ac output voltage that is linearly proportional to the magnitude of the position displacement.

Since the proposed system is a closed loop with magnetic ferrite materials, magnetic circuit equations are simple. The induced magnetic flux $\phi$ in the position-detecting coil is given by Eq. (5):

$$\phi = \mathcal{P} \cdot \mathcal{J},$$  

where $\mathcal{J}$ is the magnetomotive force and $\mathcal{P}$ is permeance. If $N_1$ is the number of turns of the driving coil and $i_1$ is the exciting current of the driving coil, then magnetomotive force is given by

$$\mathcal{J} = N_1 \cdot i_1.$$  

Permeance is determined by the form of the system. Figure 5 shows the flux paths near the air gaps. Path 1 is the...
shortest route from the fixed magnetic blocks and movable cores. Path 2 is the other route from the fixed magnetic blocks and movable cores except path 1, whereas the flux along path 3 does not pass through the movable cores and does not produce induced voltages in the position-detecting coils. If the air gap \( l_g \) is sufficiently small compared to the core length \( l_c \), flux exchange occurs, for the most part, via path 1. The fluxes along paths 2 and 3 introduce nonlinearity. Only path 1 is included in the following equations. As shown in Sec. III the measured nonlinearity is very small. Flux separation by the cores is proportional to the overlapping area changes between the magnetic materials near the small air gaps. Each area change is from \( h x_0 \) to either \( h (x_0 + \Delta x) \) or \( h (x_0 - \Delta x) \) in Fig. 5. Here, the defined permeance of the system is given by

\[
\mathcal{P} = \frac{\mu A}{2 l_g},
\]

where \( \mu \) is the permeability, \( l_g \) is the air gap, and \( A \) is the overlapping area between the \( E \)-type magnetic materials and the cores. In this case, \( A \) is given by \( h (x_0 + \Delta x) \) and \( h (x_0 - \Delta x) \) at each of the cores. The generating flux in each core is

\[
\phi_1 = N_1 i_1 \frac{\mu_0 h (x_0 + \Delta x)}{2 l_g},
\]

\[
\phi_II = N_1 i_1 \frac{\mu_0 h (x_0 - \Delta x)}{2 l_g},
\]

where \( N_1 \) is the number of turns of the driving coil, \( i_1 \) is the input current, \( \mu_0 \) is permeability, \( h \) is the core’s height, \( l_g \) is air-gap size, \( x_0 \) is initial overlap length, and \( \Delta x \) is the cores’ movement along with the input position. The position-detecting coils are connected to yield a differential output. The induced voltage in the position-detecting coil is

\[
\nu_{diff} = -N_2 \frac{d \phi}{dt} = -\frac{N_1 N_2 \mu_0 h \cdot \Delta x}{l_g} \cdot \frac{di_1}{dt},
\]

where \( N_2 \) is the number of turns of the position-detecting coil. The transfer function is given by Eq. (11), where the input voltage \( \nu_{in} = L_i d i_1 / d t + R_1 i_1 \)

\[
\frac{V_{diff}(s)}{V_{in}(s)} = -\frac{N_2}{N_1} \frac{\mu_0 h \cdot \Delta x}{l_g} \cdot \frac{s}{s + R_1}.
\]

The generated differential voltage is a function of the movement of the core \( \Delta x \). That is, the core’s movement is proportional to the input position and thus the generated voltage is proportional to the input position. The sensing system thereby produces an output signal proportional to the input position. Here, the elements that affect the system characteristics and sensitivity are the turns ratio, the air-gap size between the fixed magnetic blocks and movable cores, the capacitance effect, the excitation frequency, and so forth. The initial overlap length \( x_0 \) is determined by considering its measurement range. The system parameters are observed and the improvement of characteristics is attempted by performing experimental tests.

III. EXPERIMENTAL RESULTS

The experiment was first performed by varying the turns ratio. Figure 6 shows frequency responses according to variations in the turns ratio. To test the proposed system, a dynamic signal analyzer (HP35670A) was used. The range of the source frequency was from 1 to 40 kHz. The source input was a 1.0Vpp sinusoidal ac wave and the system output

![FIG. 5. Flux paths near the air gaps.](image)

![FIG. 6. Experimental results I: frequency responses according to turns ratio.](image)

![FIG. 7. Experimental results II: frequency responses according to air-gap dimensions.](image)
is the differential output of the position-detecting coil. The signal analyzer measures frequency responses between the source input and a differential output. The number of turns in the driving coil is limited by the allowable maximum current of the source; at which 150 turns is selected. To obtain the high sensitivity, a high turns ratio is advantageous, but the system response must not be affected by the LC resonance in the commonly used frequency range. The gain increase due to the LC resonance is very sensitive to the environment. As the number of the position-detecting coil turns increases, the inherent capacitance component increases and LC resonance frequency moves to a lower frequency. Thus the number of turns of the position-detecting coil is limited. In the case of 250:150 and 450:150 turns ratios, the frequency response is nearly not affected by the LC resonance in the commonly used frequency range. For the 750:150 turns ratio, the frequency response is affected by LC resonance in several kHz frequency regions. If the turns ratio is further increased, the LC resonance point will move down to a lower frequency, and then, the frequency response is affected by LC resonance at the commonly used frequency. The turns ratio of 750:150 is adopted as that at which the highest sensitivity is obtained considering its operating frequency.

Figure 7 shows the results of gain increase according to the air gaps, where gain is defined as output voltage divided by the driving voltage. Optical stages with micrometers are used to adjust the air gaps and set up experimental conditions like the input position. Tested air gap sizes were 0.15, 0.20, 0.30, 0.40, 0.50, 0.60, 0.80, and 1.00 mm. As the air gap decreases, the gain increases. As the air gap decreases, however, the system becomes more difficult to construct. In the case of 0.15 mm, the system is influenced by the resonance. It is difficult to maintain the gap between fixed magnetic blocks and movable cores in the micron range. In practical use, an appropriate guide mechanism is strongly considered to maintain a narrow air gap.

Figure 8 shows output data according to the source frequency; alternating currents of 2.5, 5, and 10 kHz are used as the source frequency. The selected parameters based on the previous experimental results are 750:150 turns ratio and 0.20 mm air-gap size. System responses are obtained at discrete steps of 0.05 mm. For each measured data point, curve fitting is performed using the non-negative least square fitting method. Table I shows the obtained values. The results are a sensitivity of 2200–2800 mV/V mm and linearity error of ±0.029%–0.097% in the range of ±200 μm.

<table>
<thead>
<tr>
<th>Source frequency (kHz)</th>
<th>Sensitivity (mV/V/mm)</th>
<th>Null voltage (mV)</th>
<th>Linearity error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>2188.65</td>
<td>0.5005</td>
<td>0.029</td>
</tr>
<tr>
<td>5.0</td>
<td>2289.70</td>
<td>1.5465</td>
<td>0.075</td>
</tr>
<tr>
<td>10.0</td>
<td>2779.54</td>
<td>-3.5747</td>
<td>0.097</td>
</tr>
</tbody>
</table>
Repeatability means the ability of a system to reproduce output readings when the same measured value is applied to it consecutively. Figure 9 shows the repeatability of the test results. The signal amplifier was used and amplified gain is about 10. We tried 150 times and the obtained result presents a repeatability of 46 nm (standard deviation).

IV. DISCUSSION

The newly proposed precision magnetic position-sensing system is discussed. The system is designed for detection in the submicron range. A symmetric and closed loop form is chosen to generate strong flux and to reduce the flux loss. The appropriate turns ratio is selected to provide high sensitivity, considering LC resonance. The important elements that affect the system characteristics and sensitivity are the turns ratio, the air gaps between the fixed and moving part, capacitance effect, and excitation frequency. The test results show that the sensitivity was greater than 2000 mV/(V mm), with a linearity error below ±0.10% over a ±200 μm range, and repeatability below 50 nm standard deviation. The magnetic position sensing system developed here can be applicable to many types of position or surface measurement systems.

ACKNOWLEDGMENT

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