Innovative Differential Hall Effect Gap Sensor through Comparative Study for Precise Magnetic Levitation Transport System

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Abstract

Three types of gap sensors, a capacitive gap sensor, an eddy current gap sensor, and a Hall effect gap sensor are described and evaluated through experiments for the purpose of precise gap sensing for micrometer scale movement, and a novel type of differential hall effect gap sensor is proposed. Each gap sensor is analyzed in terms of resolution and environment dependency including temperature dependency. Furthermore, a transport system for AMOLED deposition is introduced as a typical application of gap sensors, which are recently receiving considerable attention. Based on the analyses, the proposed differential Hall effect gap sensor is found to be the most suitable gap sensor for precise gap sensing, especially for application to a transport system for AMOLED deposition. The sensor shows resolution of 0.63 mV/µm for the overall range of the gap from 0 mm to 2.5 mm, temperature dependency of 3 µm/°C from 20°C to 30°C, and a monotonic characteristic for the gap between the sensor and the target.

Keywords: Gap sensor, Capacitive, Eddy current, Hall effect, AMOLED deposition, Transport system, Magnetic levitation

1. INTRODUCTION

Conventionally, numerous types of gap sensors, have been developed for accurate position sensing in various applications. Capacitive gap sensors utilize the variation of capacitance between two conductive materials and their main principle follows that of typical capacitive sensors. [1-7] Eddy current gap sensors measure the impedance change due to different amounts of eddy current generated between the sensor and the target object due to different displacement between the two. [8-12] Hall effect gap sensors utilize the Hall effect and measure the Hall voltage induced by the sensor and the target material for the position of the target. [13-17] In previous works, only one type of gap sensor has been dealt with. However, since each type of gap sensor has respective advantages and disadvantages, in order to select the most suitable type of sensor for a specific application, it is necessary to analyze and compare different types of gap sensors. The work in [18] includes and deals with various types of gap sensors for magnetic bearings but without any specific structure for the sensors.

In this paper, three types of gap sensors have been analyzed with experiment results and the detailed structures of the sensors have been presented, and a sensor type with a proposed structure is suggested as a suitable sensor for the application of transport system using magnetic levitation for the AMOLED deposition procedure.

2. THREE TYPES OF GAP SENSORS

2.1 Capacitive Gap Sensor

2.1.1 Principle of sensing method

Capacitive sensors are widely used to measure the position of an object or the distance between two objects. Fig. 1 shows two plates placed in parallel that form a capacitance. [1-3]

In parallel plates, the capacitance is calculated by

$$C = \frac{Q}{V} = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

where $C$ is the capacitance with stored charge $Q$ at a certain voltage $V$, and $\varepsilon_r$, $\varepsilon_0$ is the dielectric constant of the substance between the two plates and permittivity of free space, respectively, with plate area of $A$ and distance between the two plates of $d$. In a capacitive gap sensor, the sensor plate and the target form a

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parallel plate capacitance that can be exploited to measure the gap between the two.

To convert distance between the sensor plate and the target to a voltage, the sensing circuit consists of an amplifier (AD744 in our implementation), frequency generator (F.G.), AC current generating resistor \( R_C \), DC decoupling capacitor \( C_C \), feedback resistor \( R_f \), and sensing capacitor \( C_S \), as shown in Fig. 2.

When the frequency generator generates AC voltage with 5 V peak to peak, AC current that is generated by \( R_C \) flows into \( C_S \) and the output voltage of the amplifier \( v(t)_{\text{OUT, Amp}} \) swings with the same frequency as the input signal from the frequency generator. Since the induced AC current is constant due to the fixed value of \( R_C \) and the DC component from frequency generator is blocked by \( C_C \), the peak value of \( v(t)_{\text{OUT, Amp}} \) is changed along with the capacitance of \( C_S \) by (1). In other words, change of the gap between the sensor plate and the target alters the peak value of \( v(t)_{\text{OUT, Amp}} \). Since the controller at the backend circuitry requires voltage in the form of DC, \( v(t)_{\text{OUT, Amp}} \) has to be averaged by a precision rectifier with a filter. Here, the bandwidth of the filter should be designed to be sufficiently larger than the sensing speed requirement.

In designing the sensing circuit, the loop gain \( T \) in Fig. 2 should be carefully considered because it is closely related to noise reduction and stability. In our design, \( T \) was set to be as large as possible within the stable region of which the phase margin of \( T \) is larger than 0 degrees. In addition to careful consideration on \( T \), the input node of the amplifier with the sensing capacitor should be well designed with small parasitic capacitance and sufficient shielding. With large parasitic capacitance, the overall gain could be decreased and with insufficient shielding, the output of the sensor becomes very vulnerable to noise.

### 2.1.2 Experimental Results

Fig. 3 shows the output voltage of the amplifier \( v(t)_{\text{OUT, Amp}} \) and

![Fig. 3. Measured results of capacitive gap sensor from 0 to 3 mm distance range for (a) \( v(t)_{\text{OUT, Amp}} \), (b) \( v(t)_{\text{OUT, filter}} \), and reference sensing range of around 1 mm gap for (c) \( v(t)_{\text{OUT, Amp}} \), (d) \( v(t)_{\text{OUT, filter}} \).](image)
filter \(v(t)_{\text{OUT}}\) with respect to the distance, i.e. the gap, respectively, when the gap is increased from 0 to 3 mm. As the gap between the sensor plate (50×50×5 mm aluminum) and the target (50×50×5 mm aluminum) increases, \(v(t)_{\text{OUT}}\) also increase because the capacitance of the sensing capacitor decreases, as mentioned above. Furthermore, \(v(t)_{\text{OUT}}\) and \(v(t)_{\text{OUT, filter}}\) are highly linear when the gap is changed with a unit step of 5 \(\mu\)m around the 1 mm reference gap region. It can be seen that the \(v(t)_{\text{OUT, filter}}\) is changed with 1.3 mV per 1 \(\mu\)m variation of the gap.

Fig. 4 shows the temperature characteristic of the capacitive sensor at the reference sensing region of displacement (at 1 mm). Temperature variation resulted in 2.5 mV per 1°C or effectively 3.25 \(\mu\)m per 1°C from 20°C to 30°C. As shown in the figure, \(v(t)_{\text{OUT, filter}}\) is varied with respect to the temperature, where the varying curve is non-monotonic because the sensor consists of various components such as resistors, capacitors, an amplifier, and a rectifier, which have different temperature coefficients.

2.2 Eddy Current Sensor

2.2.1 Principle of sensing method

Eddy current sensors are generally used to measure the displacement of a conductive material. \[8-12\] Fig. 5 shows the principle of an eddy current gap sensor and simplified circuit modeling of the eddy current gap sensor. \[8\]

As shown in the figure, ac current is first applied at the sensor coil from the sensor electronics. Due to the ac current of the sensor coil, eddy current is generated at the conductive or metallic target. The generated eddy current then affects the impedance of the sensor coil and the amount varies depending on the gap. For the calculation of the gap, sensor electronics sense the impedance of the sensor coil. Here, the metallic target can be modelled as an inductor and a resistor connected in parallel, and the sensor coil as an inductor and a resistor connected in series. When simplified, the configuration as a whole can be modelled as a gap varying inductor and resistor connected in series. \[8\]

The sensor circuit structure of an eddy current gap sensor is shown in Fig. 6, with specific component names and values of passive elements utilized in our sensor implementation. The first stage is an inductance-to-frequency converter (IFC). \[8\] Depending on the gap \(x\), the inductance of the coil varies, and this varies the frequency of the output. In detail, as the gap decreases, larger eddy current is generated to decrease the effective inductance of the coil, which then increases the resonant frequency, i.e. the output frequency, formed by the effective inductance and \(C_p\). The second stage is composed of a frequency-to-voltage converter (FVC). The frequency information from the first stage is converted to voltage, and therefore the voltage varies depending on the gap between the coil and the target. The last stage is the amplifier stage, which amplifies the voltage from the second stage and eventually increases the overall sensitivity (mV/\(\mu\)m) of the gap sensor.

In constituting an eddy current gap sensor, there are some
important considerations for proper operation. In terms of the target, the target size should be larger than three times the sensor coil’s diameter and its thickness should be over two times its skin depth. In addition, it should have high conductivity and low magnet permeability. In terms of the sensor coil, it is preferred to have lower resistance. Lastly, the operating frequency should be below 1/3rd of the self-resonant frequency due to the parasitic capacitance of the coil and cable in the sensor. [8]

2.2.2 Experimental Results

Important parameters of the eddy current gap sensor implemented and used in the experiment are shown in Table 1.

Fig. 7 shows the overall results of the eddy current gap sensor’s final output with respect to distance (gap) from 0 to 2.5 mm. As shown in the figure, the final output has a negative slope with respect to the gap because the frequency output of IFC and the voltage output of FVC decrease as the gap increases due to the increased effective \( L \) of the coil by the decreased eddy current. The resolution results in 1.8 mV per 1 \( \mu \)m in the overall sensing region and 2.3 mV per 1 \( \mu \)m in the reference region of displacement (~ 1 mm).

Fig. 8 shows a temperature characteristic of the eddy current gap sensor at the reference region of displacement (at 1 mm). Temperature variation resulted in 55 mV per 1°C or effectively 24 \( \mu \)m per 1°C from 20°C to 30°C.

2.3 Hall Effect Sensor

2.3.1 Principle of sensing method and the proposed sensor

Hall effect sensing is a useful sensing method to sense the location of a gear and motor, current in a power train, speed of a disc, etc. [13-17] The Hall effect generates a force by applying a magnetic field to a conductor with a current flow. The generated

![Table 1. Conditions of eddy current gap sensor.](image)

![Fig. 7. Measured results of final output of eddy current gap sensor with respect to the gap for (a) all gap range from 0 to 2.5 mm and (b) around the reference gap region of 1 mm.](image)

![Fig. 8. Measured results of temperature characteristic of the eddy current gap sensor at 1 mm gap.](image)

![Fig. 9. Principle of a Hall effect gap sensor.](image)
force is orthogonal to the current and the magnetic field and induces a certain voltage, i.e. Hall voltage, as shown in Fig. 9. With this principle of the effect, a Hall effect sensor can be also used to sense the distance between the sensor and a certain target. A typical Hall effect gap sensor consists of simple components such as a Hall effect sensor and a magnet, and thus the cost for manufacturing the gap sensor is very low compared to that of other gap sensors with high sensitivity. However, conventional Hall effect gap sensors have a limitation with respect to interference of the ambient magnetic field, which disturbs precise gap sensing. Therefore, a scheme to remove magnetic field noise is necessary for the sensor.

2.3.2 The proposed differential Hall effect gap sensor

The proposed differential Hall effect gap sensor to compensate for the ambient magnetic field noise can be modeled as shown in Fig. 10.

The proposed gap sensor consists of a U-shaped magnet and two Hall sensors located at the center of the magnet facing the target (iron), as shown in Fig. 10(a). In the configuration of Fig. 10, as the distance between the target and the measurement point is changed, the magnetic flux density \( B \) is also changed by (2),

\[
B = \frac{V_f}{R_1 + R_2 + 2R_d} = \frac{V_f}{2R_d} = \frac{V_f}{2} \cdot \frac{\mu_r \cdot \mu_o \cdot A}{l} \tag{2}
\]

where (2) is characterized by
- \( V_f \): magnetic potential
- \( \mu_r \): magnetic permeability
- \( \mu_o \): permeability of free space
- \( A \): cross section area
- \( l \): gap between target and magnet
- \( l_{mg} \): distance between measurement point
- \( w \): width
- \( h \): height
- \( R_1 \): magnetic resistance on the target
- \( R_2 \): magnetic resistance on the magnet
- \( R_d \): magnetic resistance in the free space.

The proposed Hall effect gap sensor cancels out common noise and thereby removes the ambient magnetic field. Furthermore, sensitivity is increased twofold because of the differential sensing scheme. Through pre-setting of the Hall effect sensors \( H_1 \) and \( H_2 \), which are programmable sensors, \( H_1 \) and \( H_2 \) have identical characteristics except the slope, which is the opposite, with respect to magnetic field. Therefore, the output voltages of the hall sensors, \( V_{OUT,1H} \) and \( V_{OUT,2H} \), vary in the same direction as the

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Fig. 10. (a) Simplified structure of the proposed differential Hall effect gap sensor with (b) summing circuit.

Fig. 11. Simulation results of (a) magnetic flux density variation with respect to \( w \), (c) 2D graph of orthogonal and lateral element of magnetic flux density for different \( w \) values and (c) magnetic flux density variation with respect to gap for 5 different \( w \) values.
variation of distance between the Hall effect sensors and the target, while they vary in the opposite direction with respect to the common interference. The next stage is the summing circuit, as shown in Fig. 10(b). The summing circuit generates one output voltage \( V_{\text{OUT, Sum}} \) by summing \( V_{\text{OUT, HI}} \) and \( V_{\text{OUT, LO}} \), and as a result, common interference of a magnetic field is canceled out and sensitivity is increased. To sense the gap more precisely, the structure of the magnet has to be optimized. Fig. 11 shows the simulation result of \( B \) with \( w \) and gap. With certain \( l_{mg} \) and \( h \) values of Fig. 11(a), the amount of the orthogonal and lateral element of \( B \) varies with \( w \), as shown in Fig. 11(c). Specifically, \( B \) is concentrated on the measurement point for small \( w \) values while the absolute amount is small. On the other hand, as \( w \) increases, the total amount of \( B \) increases while \( B \) is rather diffused. Furthermore, the magnet length \( (l_{mg}) \) should also be optimized because a long \( l_{mg} \) increases \( R_{2} \) of Fig. 10 while short \( l_{mg} \) causes interference of \( B \) between the two faces of the magnet that face the target. Fig. 12 shows variation plots of \( B \) with respect to \( l_{mg} \).

To increase the sensitivity of the gap sensor based on the Hall effect, the amount of \( B \) at the measurement point has to be large and concentrated. Therefore, based on the results of the simulation presented in Fig. 12, \( l_{mg} \) of our Hall effect gap sensor was chosen to be almost twice \( w \).

### 2.3.3 Simulation and Experimental Results

In our implementation and experiment, to improve ambient magnetic flux noise immunity, the proposed differential Hall effect gap sensor was shielded by a magnetic material. Fig. 13 shows the output voltage of the Hall effect gap sensor \( (V_{\text{OUT, Sum}}) \) in the range between 0 to 2.5 mm. As shown in the figure, \( V_{\text{OUT, Sum}} \) is decreased as the gap is increased because the magnetic resistance in the free space is increased by (2), where the gap is the distance between the surface of the Hall effect sensors and the target (50 x 50 x 5 mm iron). The slopes of the output voltages along with the gap in Fig. 13 are different for two cases with different distance between the two faces of the magnet \( (d=l_{mg}-w) \). Sensitivity resulted in a higher value around the reference gap region of 1 mm (0.63 mV/μm) for \( d=10 \) mm than
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3. GAP SENSOR APPLICATION:
TRANSPORT SYSTEM USING MAGNETIC LEVITATION

In this section, a representative application for a precise gap sensor is described in detail regarding the environment, conditions, and required specifications.

3.1 Transport system using magnetic levitation for AMOLED deposition

Recently, AMOLEDs are increasingly being used for displays because of their superior characteristics such as high contrast ratio, wide viewing angle, and natural color. Following this trend, there is a high demand for manufacturing large size displays using AMOLEDs. However, an important issue arises from the deposition process of large size AMOLED displays due to the relatively small mask area compared to the total area of the display. Since the deposition of an AMOLED requires a very precise procedure, a transport system using magnetic levitation is adopted as a solution. Adopting the transport system using magnetic levitation, the position of the relatively small-area mask is fixed while precise (<±10 µm) movement of the glass is applied above the fixed mask utilizing magnetic levitation for full AMOLED deposition of the display. In order to enable precise movement of the glass, precise position control, speed control, and most importantly, accurate position sensing of the glass is mandatory. Therefore, there is high demand for precise gap sensors to enable accurate and precise position sensing.

3.2 Structure and environment of transport system

Fig. 15 shows a picture of the overall structure of one type of transport system using magnetic levitation. In the real application,
the transport system is placed into a vacuum room and a glass-adhered electro-static chuck (ESC) is attached below the carrier for deposition of the AMOLED.

A simplified figure depicting the deposition of an AMOLED with the levitated carrier is shown in Fig. 16. The position of the mask is fixed and the glass-adhered carrier is moved through levitation for the deposition of the AMOLED via radiant heating. For accurate deposition of the AMOLED, the temperature of the whole system is maintained around the room temperature while the variation is limited below 1°C in order to prevent dimension change of the carrier and other parts of the transport system due to the varying temperature.

3.3 Specifications of Gap Sensor for the Transport System

Table 3 shows the specifications of the gap sensor for the transport system with magnetic levitation.

As can be seen from Table 3 and Fig. 15, for accurate gap sensing, numerous sensors are needed in a single transport system. Generally, for accurate levitation control, sensors should be located with 250 mm distance between every two adjacent sensors. Repeatability error is the error between the sensed position and the absolute position when the carrier returns to its original position after a gap change or when there is a change in temperature. The specification for the sensing speed is determined considering the control loop speed of the total system, which is ~2 kHz. Lastly, since numerous sensors are needed for a single transport system, small size and low price of the gap sensor is also necessary.

4. DISCUSSION

In this section, a comparison between the three types of gap sensors is given considering the application of a transport system using magnetic levitation for AMOLED deposition.

Table 4 summarizes six main performance measures of the three types of gap sensors.

Resolution in the comparison table is calculated considering the fact that a typical commercial gap sensor, AEC-5505, regards a 2 mV change of the output as the gap sensor’s resolution. With all of the gap sensors having resolution below 5 µm, the resolution specification is satisfied for all three types while the eddy current gap sensor resulted in the highest resolution. In terms of temperature dependency, taking the maximum temperature variation of the system as 1°C, repeatability error of <5 µm is satisfied for the capacitive and proposed Hall effect gap sensors while the eddy current gap sensor experiences larger variation than the repeatability error specification. In terms of sensing speed, bandwidth experiments were conducted and three types of gap sensors all exceeded the sensor speed specification of 10 kHz.

Also, all types of gap sensors, including the proposed differential sensing Hall effect gap sensor that cancels out the common magnetic field, satisfy the requirement for ambient magnetic field robustness. Vacuum exposure is included in the performance comparison since it is directly related to complexity and cost of sensor design. In a real system where the transport system as a whole is put into a vacuum room, all circuit components of the system including the electromagnet and sensor electronics are

| Table 3. Specifications of gap sensor. |
|---------------------------------------|
| Article | Target Spec. |
| # of Sensors | 1 per every 250 mm |
| Max. Sensing Range | 2.5 mm |
| Main Sensing Range | 1 mm |
| Resolution | < 5 µm |
| Repeatability Error | < 5 µm |
| Sensing Speed | > 10 kHz |

| Table 4. Performance comparison of gap sensors. |
|-----------------------------------------------|
| Capacitive Gap Sensor | Eddy Current Gap Sensor | Proposed Hall Effect Gap Sensor |
| Resolution (All Range) | 1.8 µm | 1.1 µm | 4.2 µm |
| Resolution (Main Range) | 1.5 µm | 0.9 µm | 3.2 µm |
| Temperature Dependency | 3.25 µm/°C | 24 µm/°C | 3 µm/°C |
| Sensing Speed | > 10 kHz |
| B Field Effect | No effect | No effect | Cancellation |
| Vacuum Exposure | Required | Required | Unnecessary |
stuffed into an atmospheric pressure box. Here, since the box is typically made of a metallic or conductive material, the sensor plate of the capacitive gap sensor and the sensor coil of the eddy current gap sensor need to be exposed to vacuum for gap sensing. This requires a special manufacturing process and therefore increases the sensor design complexity as well as cost. Meanwhile, since the existence of a metallic but non-magnetic material between the magnet and the target does not affect the operation of the proposed Hall effect gap sensor, all the sensor components of the Hall effect gap sensor could be included in the atmospheric pressure box.

Comparing the performance of three types of gap sensors from actual experiments, it is found that the proposed Hall effect gap sensor, which satisfies specifications on resolution, repeatability error from temperature variation, sensing speed, magnetic field robustness, and no need of exposure to vacuum for low design complexity and cost, best suits the gap sensor for a transport system using magnetic levitation for the AMOLED display deposition.

5. CONCLUSIONS

In this paper, three types of gap sensors are analyzed with the detailed sensor structure and actual experiment results. The capacitive gap sensor shows relatively high resolution and low temperature dependency. However, the sensor circuit is relatively sensitive to noise and parasitic capacitance, and exposure of the sensor plate of the sensor to the vacuum is inevitable for applications that require vacuum rooms and this increases design complexity and cost. The eddy current gap sensor shows the highest resolution, whereas the output of the sensor strongly depends on temperature. Furthermore, the sensing tip or coil of the sensor should be exposed to the vacuum. Lastly, we proposed a differential sensing Hall effect gap sensor for the cancellation of ambient magnetic field noise. It shows relatively low resolution compared to the other two types of gap sensors. However, most importantly, all the sensor components could be stuffed into the atmospheric pressure box with no exposure to the vacuum for low cost and low design complexity. A transport system using magnetic levitation for AMOLED deposition is introduced as a representative application for gap sensors. We suggest our proposed hall effect gap sensor as the most suitable gap sensor for the application since it satisfies specifications on resolution (<5 μm), repeatability error from temperature variation (<5 μm for 1°C variation), sensing speed (>10 kHz), magnetic field robustness, and no need of exposure to vacuum for low cost and low complexity of sensor design.

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