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LINEAR POSITION SENSING USING MAGNETORESISTIVE SENSORS

By
Bratland, Tamara
Product Line Manager, Magnetic Sensors
Honeywell Solid State Electronics Center
12001 State Highway 55
Plymouth, Minnesota, 55441
United States of America
Phone: 763-954-2992, fax: 763-954-2764
Email: tamara.bratland@honeywell.com

Wan, Dr. Hong
Senior Principle Magnetic Sensor Design Engineer
Honeywell Solid State Electronics Center
12001 State Highway 55
Plymouth, Minnesota, 55441
United States of America
Phone: 763-954-2619, fax: 763-954-2764
Email: hong.wan@honeywell.com

Abstract

This paper presents a non-contact, non-wear-out solution for long span absolute linear position sensing. This solution utilizes an array of magnetoresistive (MR) sensors, a magnet and signal conditioning electronics. The sensors are used to determine the position of a magnet that is attached to a moving object. In addition to mechanical benefits, this solution offers a high accuracy, low power solution. In this paper we will discuss the operating principles, system error and applications of this approach.

This approach will be beneficial in applications for linear position or displacement, LVDT replacements, proximity detection, valve positioning, shaft travel, automotive steering, brake and throttle position systems. This will be used in industries including Automotive, Aviation and Industrial Process Control.

Background

Linear position sensors play an important role in automation control where precision positioning is required. Many manufacturers are looking for new approaches to meet today's needs of high reliability and accuracy. [1]

The benefits of this approach for position sensing are a non-contact, long-lasting, solid-state design with no moving parts to wear out, and no dropped signals from worn tracks, as can occur in conventional contact-based position sensing. [2] This approach fits rugged environments, such as high temperature.

Because the angle direction of the field from the magnet is measured, it is insensitive to the temperature coefficient of the magnet, is tolerant to large air gap between magnet and sensor array and is less sensitive to shock and high vibration.

This approach consists of an array of magneto-resistive sensors and a moving magnet object, shown in Figure 1. Magnetoresistive sensors bring an unique feature to this solution by measuring the angle direction of a field from a magnet versus the strength of a magnetic field. A permanent magnet provides the magnetic field, which has the function of keeping the sensors in saturation mode, minimizing effects of stray magnetic field and providing a linear operating range for selected sensor pairs.

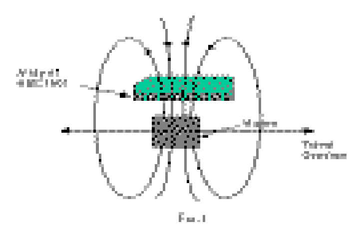

Figure 1. Linear position sensing solution

Using magnetic field as a media, the measured object attached to a magnet has non-contact with the sensor array, therefore no parts to wear out, and no lifetime limited by number of measuring cycles. Unlike the other incremental sensors, this technology is absolute reading, no reference point is required. Position is accurately known at any time as well as at power-on.

Operating Principles

This linear position sensing approach includes three elements, a array of sensors, magnet and signal conditioning electronics.

When each sensor in the array is connected to the supply voltage, it converts any ambient, or applied magnetic field to a voltage output. This device is designed to be sensitive to the direction of magnetic field when it operates in saturation mode.

The saturation mode is when external magnetic fields are above certain field strength level (called saturation field). The magnetic moments in the device are aligned in the same direction of the field. Therefore, the output of the device only reflects the direction of the external magnetic field and not the strength. The incentive of operating in saturation mode includes:

- Immunity to temperature coefficient of magnet
- Insensitivity to the gap between the magnet and the sensor array
- Insensitive to magnetic field strength when the field is greater than saturation level

The saturation field of this type of sensors is 30-50 gauss. Magnetic fields in this magnitude can be easily provided by any permanent magnet including low cost AlNiCo or Ceramic magnets, unlike Hall devices that require a stronger magnet.

$$V_{output} = V_s \cdot S \cdot \text{Sin } (2\theta) \qquad (1)$$

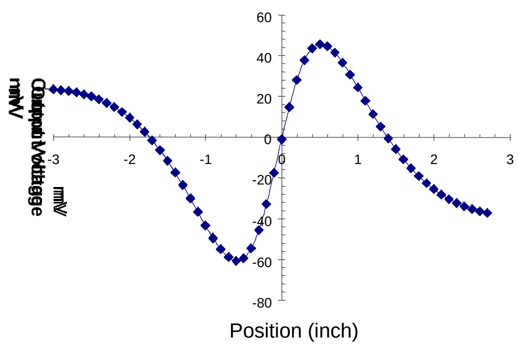

Figure 2. Single sensor output.

In saturation mode, the output of the sensor is a function of angle θ between external magnetic field and a reference direction, where V_s is supply voltage, and S is a constant related to peak-to-peak voltage (S 12 mV/V). The output of a single sensor is calculated using equation 1, and is shown in Figure 2.

A typical configuration of a magnet and sensor is mounted in the plane of X-Y, as shown in Figure 3. The north and south poles of the magnet are in the plane parallel to X-Z plane. The magnet moves along the X-axis. The sensor output in relation to magnet position is as shown in figure 2.

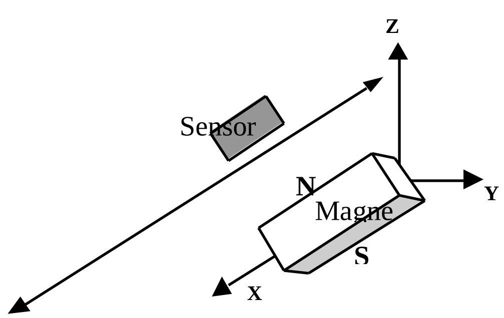

Figure 3. Typical configuration of magnet and sensor

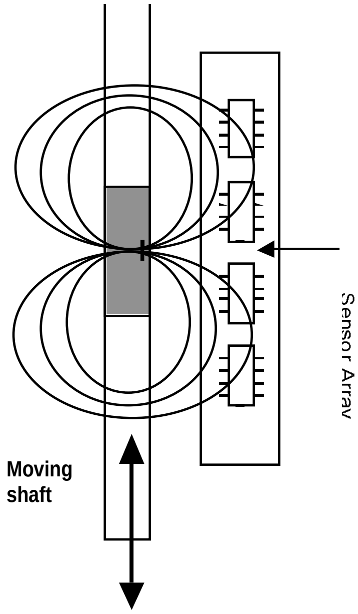

Figure 4. System design with 4 sensors

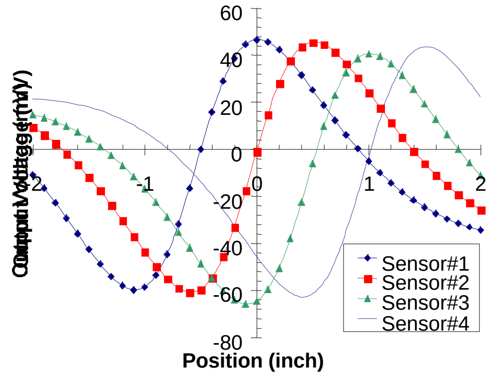

Figure 5. Output of four sensors

In the example shown in Figure 4, the output of four sensors is measured. From the outputs and the sequences of the sensors, we first locate the nearest pair of sensors to the center of the magnet. Then, the output of these two sensors is used to determine the magnet position between these two sensors. The region between minimum and maximum in the Figure 4 is usable range for position sensing. The output is better than a standard Sine function, because the magnetic field angle is not proportional.

The linear position range from this four-sensor array shown in Figure 5, is 1.5 inch long, with each sensor spaced 0.5" along the X-axis. When the magnet slides by, each sensor in the array has nearly identical output.

Sensor Array

The space between the sensors in the array is dependent on the magnet length and desired system accuracy. In principle, once the magnet length and the gap between sensor array and magnet are finalized, each sensor linear output range is determined. The space between the sensors should be half of the linear range. Because the sensor output is a sine function, the linear range of each sensor output also depends upon the system accuracy requirements. For improved accuracy the sensors should be closer together. The maximum sensor spacing is, as shown in Figure 3, the sensor #1, 2, 3 are in maximum, middle and minimum of the output curve respectively.

The number of sensors in the array is determined by traveling length, once the space between sensor is decided. Adding more sensors to the array increases the measuring length.

Air Gap

Changing the gap between magnet and sensor array only slightly decreases sensitivity and increases the linear range. Comparing it to the neighboring technologies, such as Hall sensor, it is a big advantage, because it allows larger tolerance for the air gap, easy for installation and fitting to high vibration environment. Figure 6 shows the sensor outputs at different air gaps. Even with the air gap changing 2.6mm, the linear range of the curve is almost identical. This advantage roots in the direction measurement of magnetic field vs. field strength measurements.

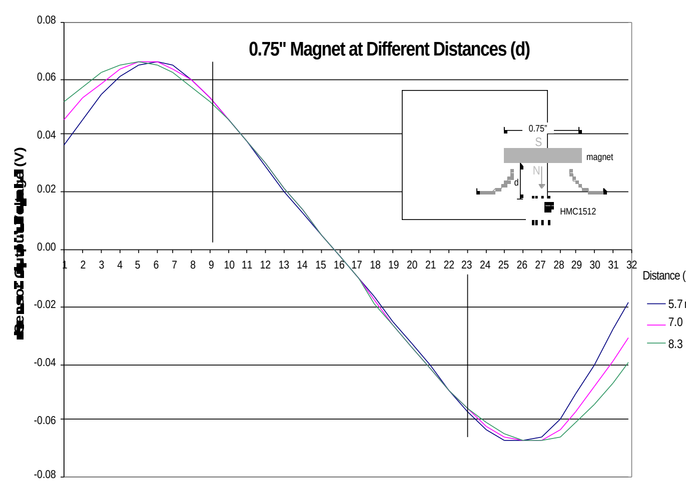

Figure 6. Variation in air gap space with same magnet

Magnet Selection

The magnet is a crucial part in the system, because it converts the motion to be measured to the sensors. The magnet is attached to the object moving, such as a valve. It is better for the magnet to be mounted with the North and South poles perpendicular to the sensor array. There are three basic requirements when selecting a magnet.

1. **Field strength -** The magnet should provide a magnetic field strong enough to maintain at least three sensors near the center of the magnet in saturation. The magnetic field could be in different directions, but the total field strength in the device plane (X-Y plane) should be higher than 30 gauss when using Honeywell sensors, for three nearest sensors at any given position. A simple dipole magnet usually has the strongest field near its poles, and field decreases with the distance. Figure 7 depicts a dipole magnet. Magnetic flux density represents the field strength of the magnet and the arrows show the direction of the field.

   For example: An AlNiCO cylinder magnet with 0.25" diameter, has a field strength 700 gauss at its surface. With a 0.25" gap between the sensor array and magnet, the field at the sensors is about 170 gauss. This is enough field strength to maintain three sensors in the saturation condition. However, if the gap increases to 0.5", the field strength is only strong enough to saturate one sensor near the center, but not enough to saturate three. A NdFeB magnet with the same dimension provides 3000 Gauss field at its surface and is able to satisfy the saturation condition at an air gap of 0.5".

2. **Magnet Size** – The geometric dimension of the magnet plays an important role in the system design. The size of magnet depends on the system requirements for measurement range and accuracy. The usable linear range of each sensor is predominately determined by the length of magnet along the moving direction. In general, changing the magnet length will result in changes of the slope of the output. A longer magnet produces a lower slope, which increases linear range of each sensor, with a trade-off of resolution or accuracy. With a shorter magnet the system has improved accuracy, but a smaller measurement range for each sensor. Of course, the system can always have longer measurement range by adding more sensors in the array.

3. **Temperature range** - Temperature coefficient of the magnet is not critical in this design approach, because the sensor output does not rely on magnetic field strength. However, in order to have accurate measurements, the magnet should be assured to provide magnetic field large enough to maintain saturation of the sensors in the whole operating temperature range.

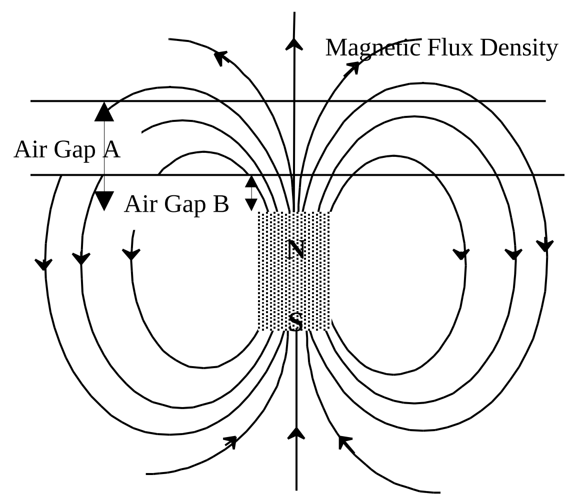

Figure 5. Magnetic Flux Density from a dipole magnet

Signal Conditioning Electronics

Figure 8 shows a basic signal condition circuit for the linear position sensor. Differential outputs from multiple sensors are connected to a multiplexer, then through a differential amplifier and A/D converter, to a micro-controller for calculating the position. Position, peak-to-peak voltage and offset voltage of each sensor are calibrated and stored in the EEPROM. The micro-controller scans the outputs from this array of sensors, then calculates the position of magnet.

To determine the magnet position, we use a linear approximation between neighboring sensors. Raw outputs from sensor s have to cancel out their offsets (V_r - V_{off}) first, then divided by their individual peak-to-peak voltage. The normalized outputs are used in the above formula.

To calibrate each individual sensor in the array, Maximum and minimum outputs of each sensor have to be recorded. The offset is half of the sum of minimum and maximum, and the peak-to-peak voltage is the differential of maximum and minimum.

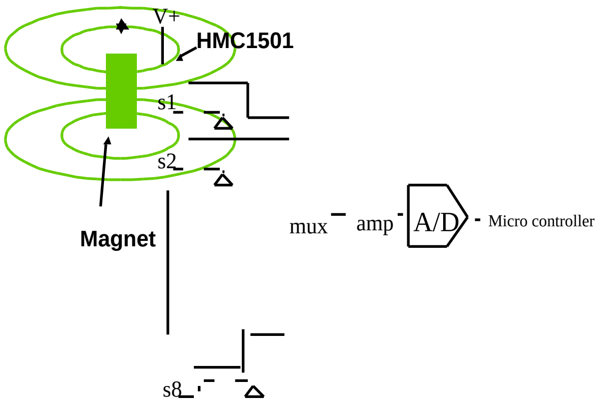

Figure 8. Signal Conditioning Block Diagram

$$V_{peak-to-peak} = V_{\max} - V_{\min}$$
$$V_{off} = \frac{1}{2}(V_{\max} + V_{\min}) \qquad (2)$$
$$V_{normal} = (V_{raw} - V_{off})/V_{peak-to-peak}$$

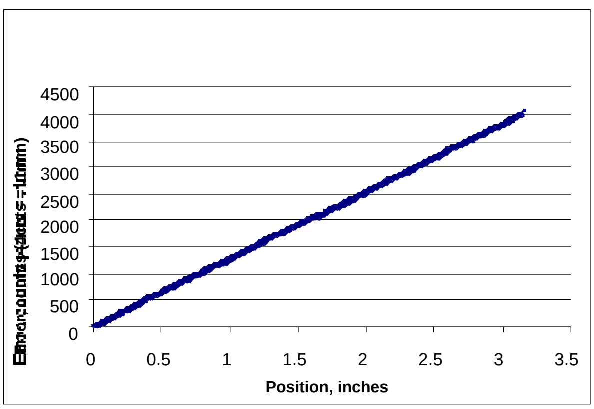

Figure 9. Final output of position sensing system after calibration

After calibration, the system output will be a linear output, as shown in Figure 9. This output can be used to determine absolute position or to feedback the controller.

System Error

Possible errors can come from the sensor array, the magnet or the signal conditioning electronics, which need to be considered in the design.

Sensor Array. Position and orientation of each sensor in the array affects accuracy of the device. These include packaged parts as well as sensor die inside of packages. In the Honeywell sensors, die position in the package has been controlled to +/-1 degree orientation and +/- 3mil from the center of package. If the position between sensors and orientation of the sensors is not controlled system errors will occur, affecting accuracy.

Magnet. If the magnet strength is not sufficient to saturate the sensor array, it will have errors, which appear like hysteresis. In the worst case, if stray fields dominate some sensor locations, the system could have random position indication or a systematic error depending on the type of stray field. Each magnet could be magnetized differently, which means the field distribution could vary from magnet to magnet, although their physical dimensions are the same. In this case, the position has an offset; it can be calibrated.

Signal Conditioning Electronics. There are several components in the signal conditioning circuitry that affect system performance. The amplifiers and A/D converter affect electrical noise and system accuracy. For example, with sensors spaced 2.5 mm apart, 0.1 mm system accuracy is achieved by using a 12 bit A/D, and it can be improved to 5µm accuracy by using a 16 bit A/D. The MR sensor has differential voltage output, an operational amplifier is recommended.

Applications

This approach will be beneficial in applications for linear position or displacement, LVDT replacements, proximity detection, valve positioning, shaft travel common in Aviation and Industrial Process Control. In automotive applications this technique can be used in steering, brake and throttle position systems. These sensors can be used in a similar approach to measure angular position.

Results

Results that have been achieved using this design are shown in table 1.

Accuracy	0.005 - 0.1mm (depending on magnet used)
Repeatability	0.002 - 0.05mm
Power Consumption	< 5mW
Magnet Size	1 – 3 cm
Travel Length	50-100mm

Table 1. Magnetoresistive Linear Position Performance Results

Conclusions

This paper presented an approach for a non-contact, absolute linear position sensing system. This approach utilizes an array of magnetoresistive (MR) sensors, a magnet and signal conditioning electronics. This solution measures the angle direction of a field from a magnet versus the strength of a magnetic field. This makes the solution tolerant to large air gap between the magnet and sensor array. This approach offers significant advantages over conventional position sensing techniques, including, a non-contact, solid state design for improved reliability, which provides a high accuracy output indicating absolute position, with insensitivity to variations in air gap using a low cost sensor.

References

[1] An interference-Based Incremental optical Encoder, Sensors Vol.17, No11, 40, 2000

[2] Linear Position Sensing Using HMC1501, Application Note 210, Magnetic Sensor, Honeywell SSEC.