Wireless Temperature Sensor Operating in Complete Metallic Environment Using Permanent Magnets

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This paper presents the first wireless temperature sensor operating in a complete metallic environment using permanent rare-earth magnets. The sensor is based on change in magnetic field strength with temperature, which is detected using commercially available Hall Effect sensors. Temperature of a hot plate at a distance of 19 mm in air and through a 9.5-mm-thick nonmagnetic austenitic stainless steel plate is successfully detected from 5°C to 80°C as a proof-of-concept demonstration. The curve fit values show excellent response with R² value greater than 98% for both the cases.

Index Terms—Magnet, rare-earth, sensor, wireless.

I. INTRODUCTION

WIRELESS condition monitoring is essential for damage identification and lifetime prediction of machine components. Wired sensors (e.g., thermocouples and strain gauges) are often suboptimal solutions due to the additional cost and inconvenience caused by the sensor’s wires. Furthermore, wired sensors may be completely impractical in applications with rotating or moving components such as bearings and mechanical seals. A variety of successful RF-based and optics-based research approaches have been presented so far in monitoring sensitive equipment [1], [2]. Both approaches are limited to components that are accessible either through optical paths (typically line-of-sight) or RF paths (not necessarily line-of-sight, but at least some openings exist). No wireless techniques are available today for machinery that is enclosed by metals.

In response to the need of wireless sensors that can be read through metal, this paper proposes a unique solution based on permanent magnets. Specifically, a temperature sensor based on neodymium magnets is experimentally demonstrated. Every permanent magnet has a temperature coefficient, i.e., its magnetic field is reduced with increasing temperature. If this change in magnetic field is measured using magnetic field sensors at a constant distance, then temperature can be recorded remotely. A constant magnetic field generated by a permanent magnet is dispersed by materials with high permeability such as iron, nickel, and cobalt. Certain types of alloy steels, however, called austenitic stainless steels have relative permeability close to unity and are widely used in machine parts. This sensor concept hence can be used for remote temperature sensing for rotating parts such as bearings and mechanical seals that are enclosed in metallic housings made up of austenitic stainless steel.

This paper is organized as follows. Section II describes various types of magnets and the Hall Effect sensor. Section III presents various test setup and results showing applicability of the sensor in an enclosed metallic environment. Lastly, Section IV discusses magnet lifetime and vibration effects.

II. MAGNETS AND MAGNETIC FIELD SENSORS

In permanent magnets, magnetism is a result of orientation of magnetic domains along a particular direction. This is achieved when magnetic materials are subjected to strong external magnetic fields leading to the formation of magnetic poles. Each of these microscopic domains is made up of 10¹⁷–10¹⁸ atoms of ferrous materials [3]. The magnetic domain orientation becomes random at elevated temperatures resulting in loss of magnetic field. An inverse effect is observed at lower temperatures with magnetic domains aligning along the direction of the poles. These effects are schematically illustrated in Fig. 1. As shown, the arrows representing microscopic domains are aligned at low temperatures with higher number of field lines traveling from N to S poles. At relatively higher temperatures, some domains have random orientation, thus reducing the number of field lines traveling from N to S poles. For certain temperature ranges depending on magnet geometry, material, and specifications, this change in magnetic domains is reversible.

![Simplified schematic showing change in microscopic domains with temperature.](image-url)
Permanent magnets such as Alnico (aluminum, nickel, cobalt), Ceramic, Nd-Fe-B (neodymium, iron, boron), and Sm-Co (samarium, cobalt) are commercially available in different sizes and shapes. These magnets are further classified in multiple grades depending upon their chemical composition and properties like temperature coefficient, energy content (B-H product), maximum operating temperature, etc. Table I gives a comparison of various magnet properties. Neodymium magnets are the strongest magnets available commercially. They have high coercivity, i.e., these magnets cannot be easily demagnetized, along with high temperature coefficient, which makes them suitable for temperature sensing applications. These magnets have Curie temperature of up to 300°C and an operating temperature range up to 200°C depending on the grade of magnet. For this proof-of-concept, N45SH grade neodymium magnet is used with a temperature coefficient of 0.11%/°C. The numerical “45” in the magnet grade notation represents the B-H product of a given magnet, while “SH” indicates the maximum operating temperature at 150°C [4]. Sm-Co magnets can be used to extend the temperature sensor range further up to 350°C.

Hall Effect sensors are widely used as position sensors in automobiles. They are based on the Hall Effect observed in certain types of semiconductor materials when subjected to a constant current and a perpendicular magnetic field. Hall Effect sensor output is highly linear with change in magnetic field and responds differently depending on the polarity of the magnet. They have limited sensitivity compared to other types of magnetic field sensors [5]. Other advantages such as minimum external signal processing circuitry, very small footprint, and operation in harsh environment make them ideal for this application compared to some of the high end methods presented in [5]. The Allegro A1395 Hall Effect sensor with sensitivity of 10-mV/G is selected for implementation of this concept. A1395 Hall Effect sensor has a small footprint of 6 mm² along with ratio-metric output depending on the magnet pole facing the sensor [6].

### III. SENSOR IMPLEMENTATION

Fig. 2 shows the sensing element that comprises a stack of five 0.8-mm-thick, 5-mm-long, 3-mm-wide N45SH grade neodymium magnets attached to a hot plate while the magnetic field is sensed by an A1395 Hall Effect sensor. These measurements cannot be performed on commonly used laboratory ceramic hot plates, as these hot plates use inductive coils for heating. These coils generate an alternating magnetic field that may affect the magnetic field sensed by the Hall Effect sensor. To mitigate this issue, sensor testing is performed on a hot-cold plate based on Peltier effect [7]. The magnet stack is attached to the hot plate using a thin double-sided tape to record its temperature. A thermocouple is also attached to the hot plate close to the magnet for reference temperature measurement, and temperature is cycled from 5°C to 80°C. The Hall Effect sensor is mounted on an aluminum support as shown in Fig. 2 at a distance of 15 mm from the magnet top surface. The distance between the magnet and the Hall Effect sensor is a tradeoff between the minimum detectable signal (depends on the specific Hall Effect sensor) and the application (how closely can the sensor be placed to the magnet). For this demonstration, we chose a distance that would be relevant for many applications, but no attempt has been made to optimize it. A detailed study that would focus on studying these tradeoffs in more detail is beyond the scope of this work. The Hall Effect sensor position is adjusted at 15 mm height to sense maximum magnetic field. This distance can be extended further to a few centimeters with small modifications in magnet geometry and test setup. The data are recorded using a multimeter, LabVIEW data logging software, and a PC [8].

The Hall Effect sensor output as presented in Fig. 3 shows excellent linear response from 5°C to 78°C range, which is significantly lower than the magnet’s Curie temperature. The curve fit value is greater than 98%. Although the magnets are rated up to 150°C, the test is limited to about 80°C due to hot-plate limitations. This response may become nonlinear as temperature approaches the magnet’s Curie temperature [3]. A minor hysteresis is observed in the sensor output, which is similar to a typical B-H curve for permanent magnets. The noise in the

<table>
<thead>
<tr>
<th>Magnet Type</th>
<th>Energy Product (MGOe)</th>
<th>Coercivity (kOe)</th>
<th>Maximum Temp. (°C)</th>
<th>Temp. Coeff. (%/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd-Fe-B</td>
<td>45</td>
<td>30</td>
<td>150</td>
<td>-0.11</td>
</tr>
<tr>
<td>Sm-Co</td>
<td>30</td>
<td>25</td>
<td>350</td>
<td>-0.04</td>
</tr>
<tr>
<td>AlNiCo</td>
<td>10</td>
<td>2</td>
<td>550</td>
<td>-0.02</td>
</tr>
<tr>
<td>Ceramic</td>
<td>4</td>
<td>2</td>
<td>300</td>
<td>-0.2</td>
</tr>
</tbody>
</table>
signal output is due to inherent noise in the Hall Effect sensor output.

Stainless steels are probably the most widely used material for machines. Steels are broadly classified into two types—namely, Martensitic and Austenitic, depending on their relative permeability. Martensitic stainless steels have high relative permeability resulting in ferromagnetic behavior similar to iron. Austenitic stainless steels have permeability close to unity [9]. To test the applicability of the sensor in an enclosed stainless steel environment, the setup shown in Fig. 4 is implemented. A 9.5-mm-thick, 316-grade austenitic stainless steel plate is placed between the Hall Effect sensor and the magnet stack without any contact to the magnets as shown. The Hall Effect sensor is directly attached to the steel plate. Furthermore, the open sides are covered using aluminum foil to leave no openings. Fig. 5 shows the sensors output with temperature for a stainless steel plate between the magnet and the Hall Effect sensor. The sensor output response is linear with temperature, which shows effectiveness of the sensor in a completely metallic surrounding. The curve fit value is close to 99%, indicating excellent sensor response.

**IV. DISCUSSION**

Sensor lifetime is an important issue that needs to be considered. While not the focus of this work, it is important to mention that permanent magnets tend to lose magnetic field with time at high temperatures. Nevertheless, as long as the operating temperature is below the magnet’s Curie temperature, the reduction in magnetic field with time is rather small. For instance, the Nd-Fe-B magnets exhibit extremely small magnetic field loss. These losses are in the order of 1%–3% from initial value as quantified by [10] at 80°C and 150°C for 10,000 hours of operation. The losses in magnetic field also depend on the permeance coefficient of the magnet. Permeance coefficient for standalone permanent magnets is dependent on magnet dimensions. For minimum losses, the magnet dimensions should be longer along the polarized direction than the cross-section dimensions. For sufficiently high permeance coefficient (>3) [11], the temperature-induced magnetic field loss is reversible. In this case, the magnets shown in Fig. 2 have permeance coefficient value 3.24, which is calculated using the method presented in [12]. Furthermore, these results show that this sensor can be used for temperature monitoring and failure detection of machines without any significant loss in magnetic field.

Another factor that may affect the sensor’s performance is mechanical vibration. The effect of mechanical vibration is dependent on the application, magnitude of vibration, and the arrangement of the Hall Effect sensor and the magnet with respect to application. Passive wireless temperature sensors for bearing cage temperature monitoring have been successfully demonstrated by [1] and [13] in vibrating environment at thousands of rpm (motor/bearing speed). These sensors are also susceptible to vibrations, but this issue has been mitigated with careful mechanical design that minimizes vibration effects. Similar designs can be readily implemented for the proposed magnetic temperature sensor.
V. CONCLUSION

The authors have successfully demonstrated the first wireless temperature sensor operating in an enclosed metallic environment. The sensor detected temperature of a hot-cold plate from 5°C to 80°C at a distance of 19 mm in air. The tests performed in a metallic enclosure showed excellent response with temperature, demonstrating the effectiveness of this sensor while operating through a 9.5-mm-thick austenitic stainless steel plate.

REFERENCES