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Pre-Magnetization Orientation Identification of Anisotropic Nd–Fe–B Magnets for Halbach-Type Motor Applications

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The orientation of anisotropic sintered Nd–Fe–B magnets is a critical factor determining their magnetic performance, and orientation misalignment can lead to significant degradation in device performance after magnetization or assembly. However, in practical manufacturing processes, it remains difficult to directly identify the preferred magnetization direction in the unmagnetized state, limiting the early detection of orientation-related defects. This challenge becomes more significant in segmented or Halbach-type magnet structures, where multiple orientation angles must be precisely controlled. In this paper, a pre-magnetization orientation identification method is proposed based on the orientation-dependent magnetic response of anisotropic Nd–Fe–B magnets under an externally applied verification magnetic field. The method utilizes Hall sensor measurements of the surface magnetic response without requiring intentional magnetization. Experimental measurements were conducted on specimens with orientation angles ranging from 0° to 90°, and the results show that the measured Hall voltage exhibits a clear and systematic variation with respect to the orientation angle. To support the observed behavior, a simplified analytical model considering the anisotropic magnetic response is developed. The model qualitatively explains the orientation-dependent trend of the measured signal, showing good agreement with the experimental results. The proposed method enables reliable identification of magnet orientation prior to magnetization and provides a practical basis for in-process inspection and automated orientation verification in magnet manufacturing.

Keywords : anisotropic Nd–Fe–B magnet, pre-magnetization inspection, easy-axis orientation, Hall sensor, permanent magnet synchronous motor, magnetic anisotropy, orientation identification

1. Introduction

Anisotropic Nd–Fe–B permanent magnets have been widely employed in high-performance electrical machines due to their high remanence and large maximum energy product. The magnetic characteristics of these materials are strongly governed by their crystallographic texture formed during field-assisted pressing and sintering processes, which defines a preferred easy magnetization direction [1, 2]. Precise control of this orientation is therefore essential to ensure the intended magnetic performance after magnetization.

In recent years, multi-directional magnetization structures such as Halbach arrays have attracted increasing attention because they enable asymmetric magnetic flux distribution, concentrating flux on one side while suppressing it on the opposite side [3, 4]. This property improves air-gap flux utilization, reduces leakage flux, and enhances overall electromagnetic performance. Consequently, such magnetization schemes have been actively applied to various electric machine topologies, including radial-flux and axial-flux permanent magnet machines, as well as optimized generator systems and rotor structures designed to improve efficiency and mitigate demagnetization effects [5–8]. In addition, the electromagnetic performance of permanent magnet machines is strongly influenced by magnet geometry, field distribution, and machine topology, which further highlights the importance of accurate magnet orientation control in practical machine design and analysis [9, 10].

A key requirement in these structures is that multiple magnet segments must be assembled with precisely defined orientation angles. Even a small deviation from the intended orientation can distort the magnetic field

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distribution, resulting in performance degradation such as increased torque ripple, reduced efficiency, or partial demagnetization [11, 12]. Unlike uniformly magnetized magnets, orientation errors in multi-directional magnetization configurations directly disrupt the intended vector magnetization pattern and are therefore particularly critical. This issue becomes even more important in advanced electrified propulsion and traction systems, where thermal reliability, winding configuration, and fault-tolerant operation are closely related to the consistency of electromagnetic characteristics [13].

From a manufacturing perspective, anisotropic Nd–Fe–B magnets are typically magnetized only at the final stage of production. Prior to magnetization, the sintered or machined magnet is nominally unmagnetized but retains strong magnetic anisotropy and a well-defined easy axis established during processing [14, 15]. In current industrial practice, orientation verification is generally performed after magnetization or during final assembly testing. However, if an orientation error is detected at this stage, corrective actions are often difficult or impossible, leading to increased scrap rates and manufacturing costs.

This limitation becomes more significant as multi-orientation magnetization structures are increasingly adopted. Since such designs require precise alignment of multiple magnet segments, there is a growing demand for a method capable of identifying the preferred orientation prior to magnetization.

Conventional magnetic characterization techniques, including B–H curve measurement and demagnetization analysis, generally require magnetized samples and are therefore not suitable for pre-magnetization inspection [2, 16]. Although magnetic sensing techniques based on Hall effect have been widely used for detecting magnetic fields [17, 18], their application has primarily focused on already magnetized materials. Hall sensors and their associated signal-processing techniques have also been extensively developed for practical sensing applications because of their compactness, linearity, and suitability for embedded magnetic measurement systems [19].

It is important to emphasize that the proposed approach is fundamentally different from conventional magnetization-based inspection methods. The method does not rely on intentional magnetization or residual magnetization of the specimen. Instead, it utilizes the intrinsic magnetic anisotropy of the unmagnetized material and its orientation-dependent response under an externally applied verification magnetic field. Although a small residual or irreversible magnetic component may exist in practice, the dominant measured response is governed primarily by the reversible anisotropic induced response associated with the easy-axis orientation. In this sense, the method should be regarded as a non-magnetizing inspection approach rather than a weak or partial magnetization technique.

When an external magnetic field is applied to an anisotropic but unmagnetized magnet, the induced magnetic response varies depending on the alignment between the applied field and the easy axis. This orientation-dependent response provides a means to infer the preferred direction without performing magnetization.

Based on this principle, this paper proposes a pre-magnetization orientation identification method for anisotropic sintered Nd–Fe–B magnets. The method employs a controlled verification magnetic field and measures the resulting surface magnetic response using a Hall sensor. By analyzing the relative variation of the measured signal, the orientation of each magnet segment can be identified prior to magnetization.

The main contributions of this work are as follows.

First, a pre-magnetization orientation identification method is proposed based on the anisotropy-driven response of unmagnetized magnets under an externally applied verification field. Second, a simplified analytical model is developed to describe the orientation-dependent behavior of the measured signal, focusing on relative trends rather than absolute values. Third, the feasibility of the proposed method is experimentally validated using Hall sensor measurements. Finally, a conceptual automated inspection framework is presented to demonstrate the applicability of the method to practical manufacturing environments.

The remainder of this paper is organized as follows. Section 2 discusses the limitations of conventional approaches for pre-magnetization orientation identification. Section 3 presents the proposed method and its analytical formulation. Section 4 provides experimental validation of the proposed approach. Section 5 concludes the paper.

2. Limitations of Conventional Pre-Magnetization Orientation Identification Approaches

The preferred magnetization direction of anisotropic Nd–Fe–B magnets is established during field-assisted pressing and sintering processes, resulting in a well-defined crystallographic texture. Although this orientation is physically embedded in the microstructure, it cannot be directly observed or quantitatively evaluated when the magnet remains in an unmagnetized state. This intrinsic characteristic makes it difficult to verify the orientation prior to magnetization.

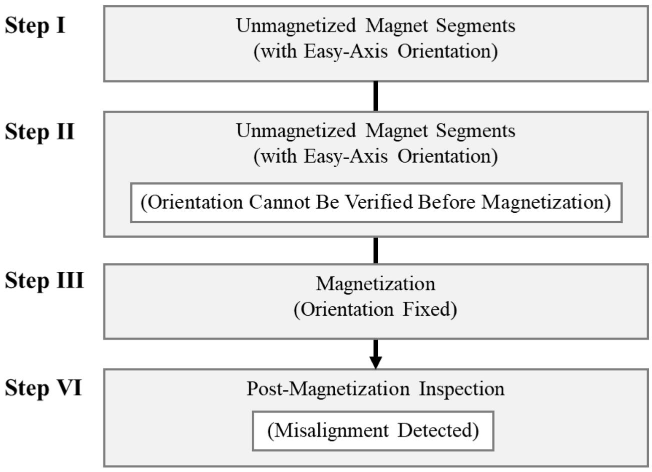


Fig. 1. Conventional manufacturing and inspection process for Halbach-type Nd-Fe-B magnets.

Fig. 1 illustrates a typical manufacturing and inspection process for Halbach-type anisotropic magnet assemblies.

The process begins with the production of magnet segments, in which the easy-axis orientation is already defined, but no macroscopic magnetization is present. These segments are then assembled into a multi-orientation structure, where each segment must be aligned according to a predefined orientation angle.

At this stage, conventional inspection methods rely primarily on geometric alignment, mechanical positioning, or visual inspection. However, these approaches can only confirm external positioning and cannot provide information about the internal magnetic orientation of each segment. Since the easy-axis direction is determined by crystallographic alignment rather than geometric features, such methods are fundamentally insufficient for reliable orientation identification.

Magnetic characterization techniques, such as B–H curve measurement and demagnetization analysis, are also not applicable at this stage because they require a magnetized specimen to produce a measurable magnetic response [13]. Similarly, magnetic field sensing techniques based on the Hall effect are widely used for evaluating magnetized structures [14], but they rely on the presence of a detectable stray field, which is absent in unmagnetized magnets.

As a result, in most industrial processes, orientation verification is performed only after the magnetization step. Methods such as surface flux measurement, Hall scanning, and performance-based evaluation based on back electromotive force and torque ripple are used to assess whether the intended magnetization pattern has been achieved. While these approaches are effective for detecting orientation errors, they are inherently post-process inspections.

A critical limitation of this approach is that the magnetization process is irreversible. Once magnetization is applied, any misalignment in the orientation cannot be corrected. Consequently, defects originating from incorrect orientation during assembly remain undetected until the final stage, leading to increased scrap rates and manufacturing costs.

Therefore, the fundamental issue is not the absence of orientation information, but the lack of a measurable physical quantity that can reveal this information prior to magnetization. This limitation becomes increasingly significant in multi-orientation magnetization structures, where even small orientation errors can significantly distort the intended magnetic field distribution. These limitations highlight the necessity of a new approach that enables orientation identification in the unmagnetized state by exploiting the intrinsic anisotropic response of the material under an externally applied magnetic field.

3. Proposed Pre-Magnetization Orientation Identification Method

In Halbach-type assemblies, each magnet segment must be placed with a prescribed orientation. Since magnetization is generally performed after mechanical assembly, an orientation error in one or more segments is often detected only after the final magnetization step. This leads to rework, yield loss, or scrap. For this reason, it is desirable to verify the orientation of each segment before magnetization.

The method considered in this work is based on a simple idea. Even before magnetization, an anisotropic magnet still has an easy-axis direction, and its magnetic response changes depending on how an externally applied field is aligned with that direction. By applying a fixed verification field and measuring the response with a Hall sensor, it becomes possible to distinguish whether each segment in an assembled Halbach structure is aligned as intended.

The overall procedure is summarized in Fig. 2. A verification field is first applied to the assembled structure.

The response is then measured along a scan direction using a Hall sensor. Because the measured signal depends on the orientation of the easy axis, a representative feature extracted from the signal can be used to identify whether the segment orientation is correct. In this work, the peak value of the measured response is used for this purpose.

A verification magnet is used to generate a repeatable excitation field. The spatial distribution of the field along

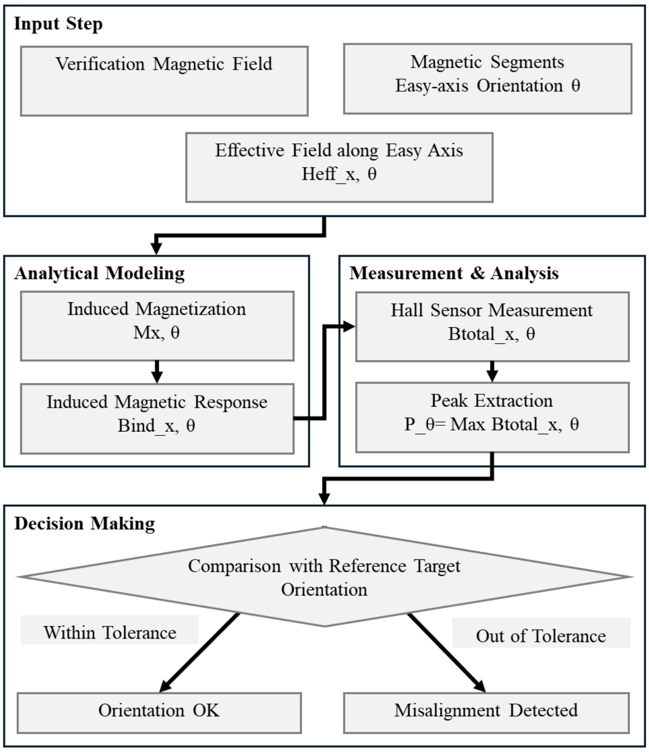


Fig. 2. Schematic flow of the proposed pre-magnetization orientation identification method for assembled magnet segments.

the scan direction x is modeled as

$$H_{vm}(x) = H_0 \exp\left[-\left(\frac{x}{\sigma}\right)^2\right] \tag{1}$$

where $H_{vm}(x)$ is the verification magnetic field at scan position x, H_0 is the maximum value of the applied field, and σ determines how widely the field spreads in space. The variable x denotes the position of the Hall sensor along the scan direction. The verification magnetic field distribution along the scan direction is approximated by the simplified form in (1). The field profile defined by (1) is shown in Fig. 3.

Equation (1) is used as a simplified and normalized field model to capture the orientation-dependent behavior, rather than to reproduce the exact field distribution of the verification magnet.

The easy-axis direction of each anisotropic magnet segment is represented by a unit vector in the x-z plane,

$$e(\theta) = \begin{bmatrix} \sin\theta \\ 0 \\ \cos\theta \end{bmatrix} \tag{2}$$

where $\mathbf{e}(\theta)$ denotes the direction of the easy axis and θ is

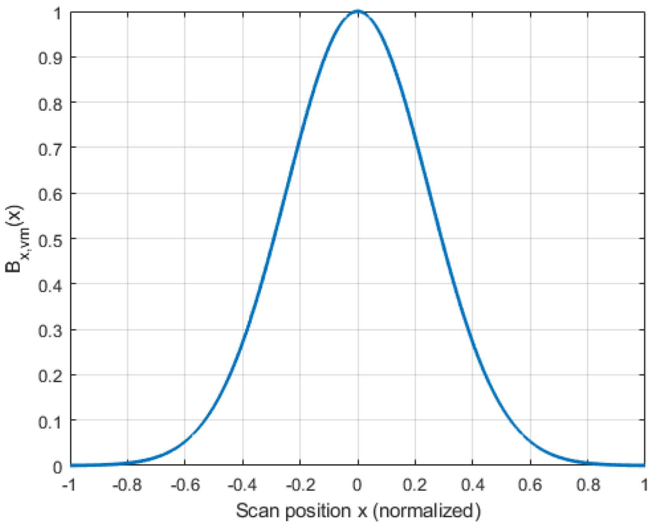


Fig. 3. (Color online) Spatial distribution of the verification magnetic field along the scan direction.

the orientation angle of that axis. The second component is zero because the easy axis is assumed to lie in the x-z plane. When $\theta = 0^{\circ}$, the easy axis is aligned with the z-direction, and when $\theta = 90^{\circ}$, it is aligned with the x-direction. This vector does not represent the magnetization magnitude itself; instead, it only describes the direction in which the material is most easily magnetized.

When the verification field is applied, only the field component along the easy axis contributes strongly to the response of the anisotropic material. The effective excitation field is written as

$$H_{\text{eff}}(x,\ \theta) = H_{\text{vm}}(x)\sin\theta \tag{3}$$

where $H_{\text{eff}}(x,\ \theta)$ is the effective field acting along the easy axis. Eq. (3) means that the same applied field can produce different effective excitation levels depending on the segment orientation. If the easy axis is more closely aligned with the scan direction, the effective field becomes larger. If it is less aligned, the effective field becomes smaller. The effective field corresponds to the component of the applied verification field along the easy-axis direction.

Before the final magnetization process, the magnet segment is assumed to have negligible remanent magnetization. Therefore, the response is described in terms of induced magnetization rather than permanent magnetization. The induced magnetization is modeled as

$$M(x,\ \theta) = k_m H_{\text{eff}}(x,\ \theta) \tag{4}$$

where $M(x,\ \theta)$ is the induced magnetization, and k_m is a proportional coefficient that represents how strongly the material responds to the effective field. A larger k_m means that a given excitation field produces a stronger induced magnetic response. Substituting (3) into (4) gives

$$M(x, \theta) = k_m H_{vm}(x)\sin\theta \quad (5)$$

Equation (5) shows that the induced magnetization depends on two factors: the magnitude of the applied verification field and the alignment of that field with the easy axis.

The Hall sensor measures the magnetic field generated by the interaction between the applied verification field and the induced response of the segment. In the present model, the induced contribution to the measured signal is written as

$$B_{ind}(x, \theta) = k_b[M(x, \theta)]^2 \quad (6)$$

where $B_{ind}(x, \theta)$ is the induced part of the measured Hall response and k_b is a gain factor that converts the induced magnetization into a measurable Hall signal. This coefficient reflects the influence of the sensing configuration, including the relative placement of the Hall sensor and the verification magnet, as well as the proportional scaling between the magnetic response and the measured output. By substituting (5) into (6), the induced response becomes

$$B_{ind}(x, \theta) = k_b k_m^2[H_{vm}(x)\sin\theta]^2 \quad (7)$$

This expression makes orientation dependence explicit. The measured induced contribution increases as the easy axis becomes more closely aligned with the scan direction.

The total signal measured by the Hall sensor is then modeled as

$$B_{total}(x, \theta) = H_{vm}(x) + B_{ind}(x, \theta) + B_{off} + n(x) \quad (8)$$

where $B_{total}(x, \theta)$ is the total measured magnetic response, B_{off} is a constant offset term, and $n(x)$ represents measurement noise. The offset term accounts for fixed bias in the sensing system, while the noise term represents random fluctuations caused by the measurement environment and sensor electronics. In the proposed method, the orientation information is identified based on the relative variation of the measured Hall response under identical measurement conditions. The calculated Hall scan signals for different orientation angles are shown in Fig. 4.

The model described above is intended to explain the relative variation of the measured signal with respect to the orientation angle, rather than to predict the absolute magnitude of the measured response.

For practical inspection, a single representative quantity is required so that the response of each segment can be compared with a reference value. In this work, the peak value of the measured signal is adopted as the main feature and is defined as

$$P(\theta) = \max\,[B_{total}(x, \theta)] \quad (9)$$

and its variation is shown in Fig. 5.

As the orientation angle changes, the peak value varies systematically, providing a basis for identifying segment alignment.

Although the absolute values obtained from the model and the experiment may differ due to practical factors such as geometry, material properties, and sensor configuration, the proposed method focuses on the consistent trend of the response with respect to the orientation. The validity of the proposed approach is therefore evaluated based on whether the same orientation-dependent trend is

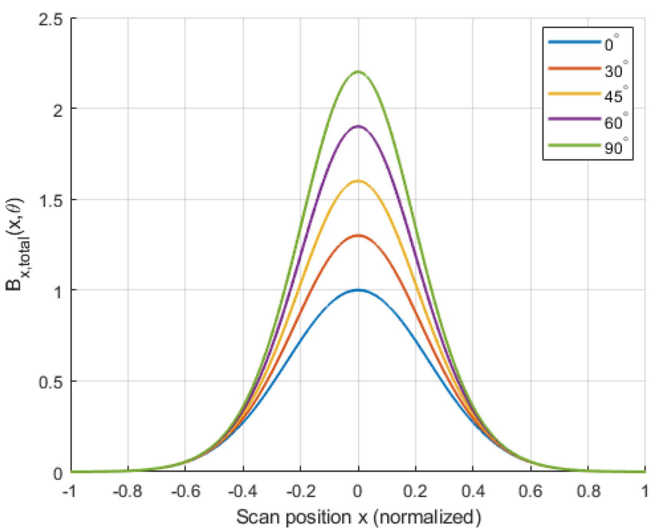


Fig. 4. (Color online) Hall sensor responses for different easy-axis orientations under the verification magnetic field.

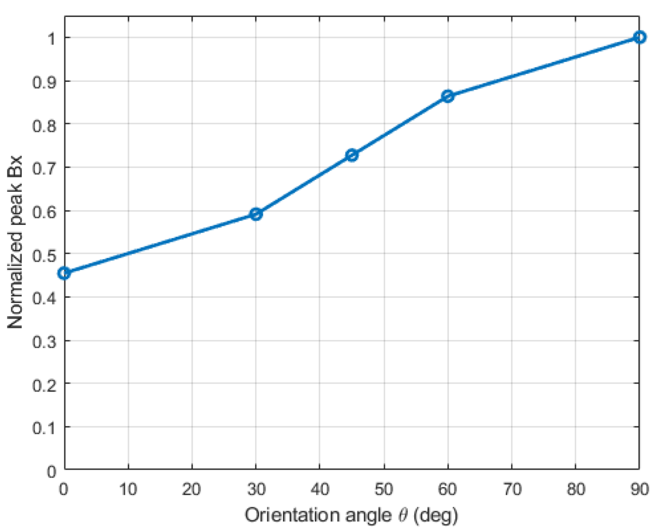


Fig. 5. (Color online) Peak Hall response as a function of easy-axis orientation angle.

observed in experimental measurements.

4. Experimental Verification

The proposed method was experimentally evaluated using a custom-built magnetic sensing system to investigate whether the orientation of an unmagnetized anisotropic magnet can be distinguished based on its measured electrical response. The purpose of this experiment is not to reproduce the exact magnitude predicted by the analytical model, but to verify that an orientation-dependent trend exists in the measured signal.

The experimental setup is shown in Fig. 6. Fig. 6(a) presents the experimental measurement setup, while Fig. 6(b) shows the schematic diagram of the Hall signal measurement and signal conditioning circuit. The system consists of a cylindrical verification magnet and a Hall sensor probe used to measure the lateral magnetic response of the test specimen. The specimens are anisotropic sintered Nd–Fe–B magnets with a diameter of 6.0 mm

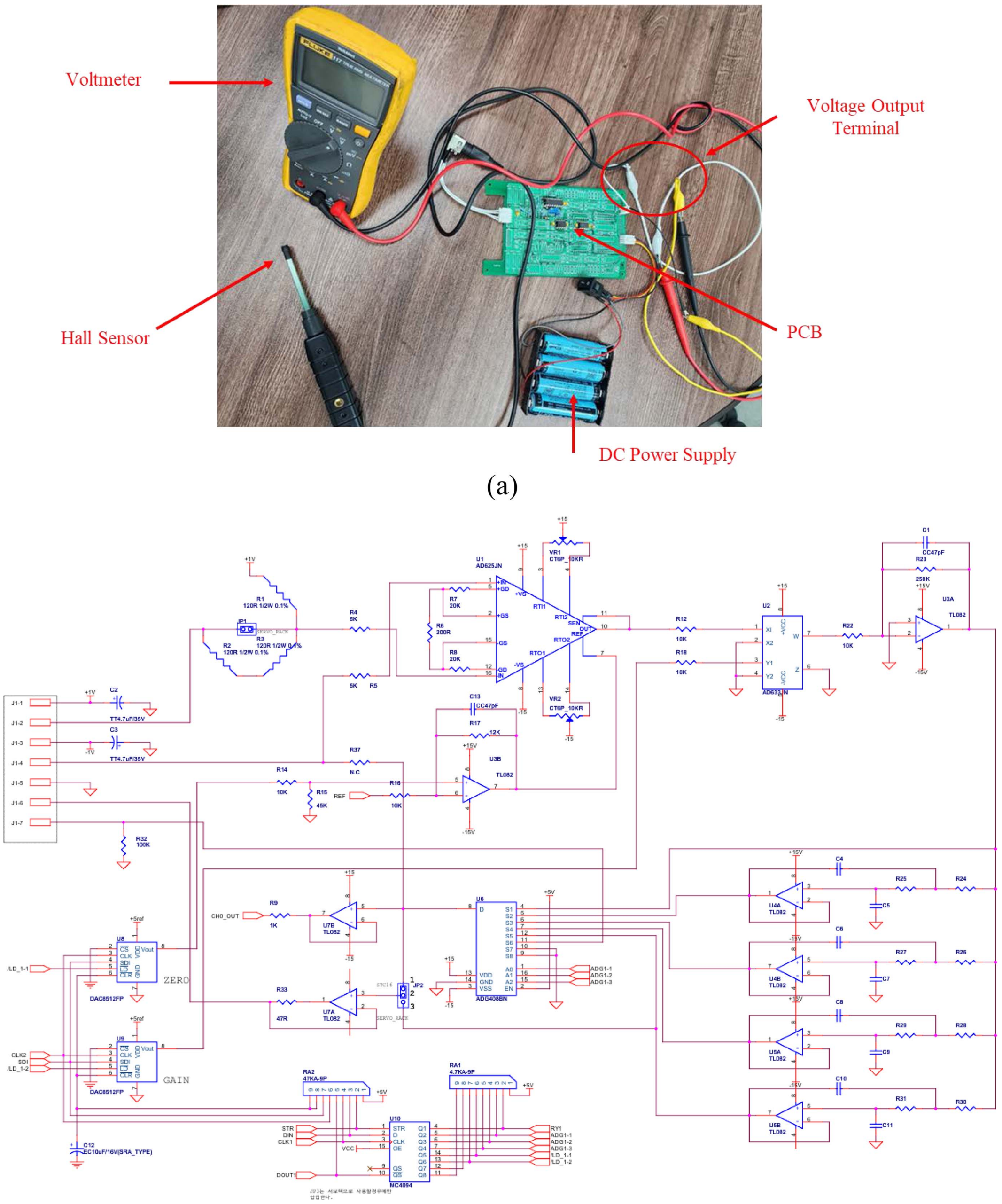
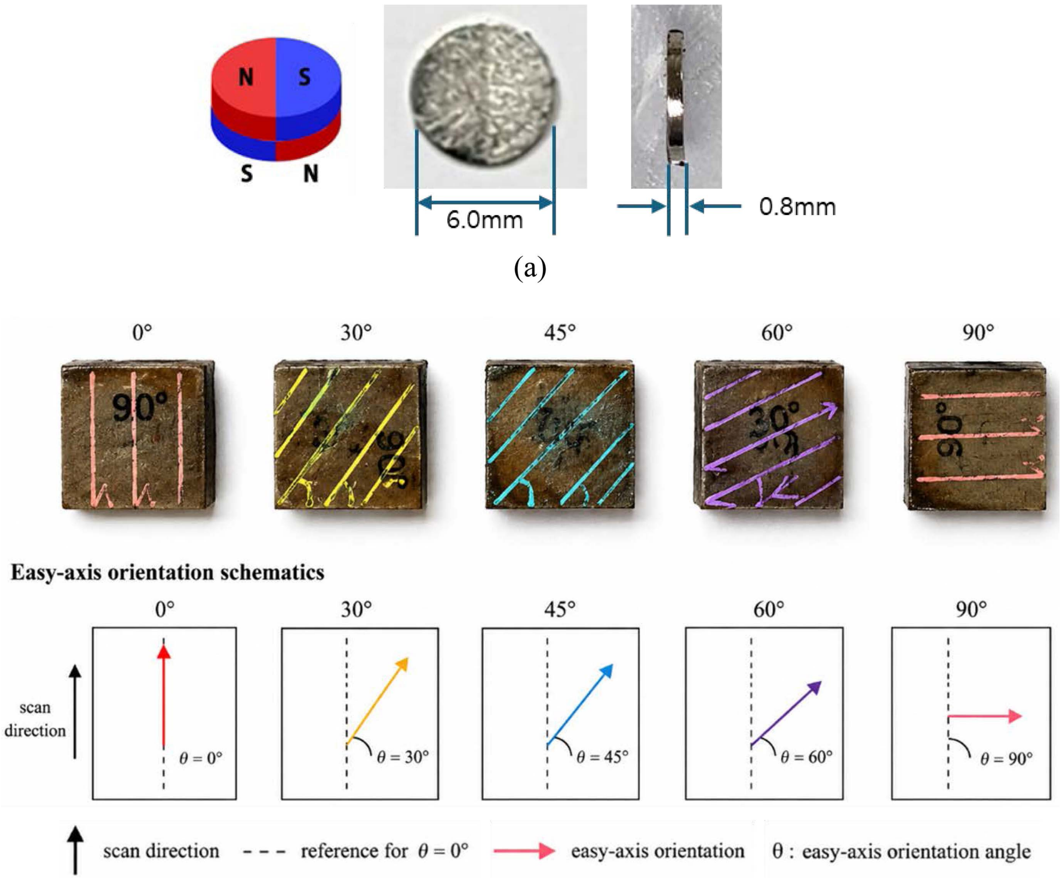


Fig. 6. (Color online) Experimental setup for Hall sensor-based measurement of unmagnetized magnet segments.



(b)

Fig. 7. (Color online) Anisotropic Nd–Fe–B magnet specimens: (a) verification magnet and specimen geometry; (b) test specimens with predefined easy-axis orientations for Hall sensor-based measurement.

and a thickness of 0.8 mm. Five samples with predefined easy-axis orientations of 0°, 30°, 45°, 60°, and 90° were prepared to evaluate the orientation-dependent behavior.

During measurement, the Hall sensor probe scans laterally across the surface of each specimen while maintaining a constant vertical distance. This ensures that all measurements are performed under consistent excitation conditions. The sensor output is processed through a signal conditioning circuit consisting of a Wheatstone bridge and amplification stages, and the resulting signal is recorded as a voltage corresponding to the magnetic response.

The test specimens with predefined easy-axis orientations used in the experiment are shown in Fig. 7. Fig. 7(a) presents the geometry of the verification magnet and specimen, while Fig. 7(b) shows the test specimens with predefined easy-axis orientations and the corresponding orientation schematics used in the measurements.

The maximum voltage observed during each scan is extracted as a representative feature corresponding to the orientation. The measured peak voltages are presented in Fig. 8. As the orientation angle increases from 0° to 90°, the measured voltage increases monotonically.

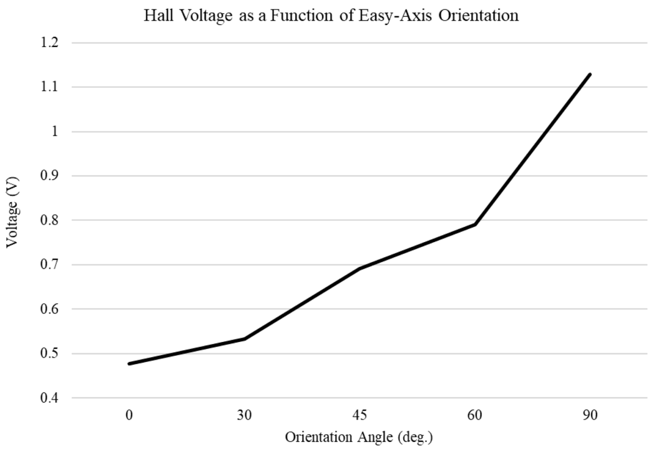


Fig. 8. Measured Hall Voltage as a Function of Easy-Axis Orientation Angle.

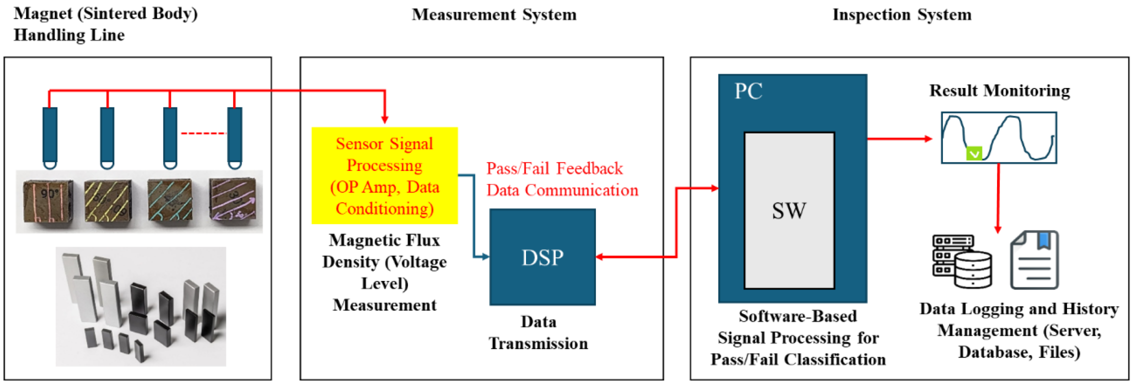


Fig. 9. (Color online) Conceptual configuration of an automated inspection system for pre-magnetization orientation verification.

This systematic monotonic variation indicates that the measured response is strongly correlated with the anisotropic easy-axis orientation. This monotonic behavior confirms that the measured signal exhibits a clear dependence on the orientation of the easy axis. Although the absolute values differ from those predicted by the analytical model due to practical factors such as geometry, material properties, and sensor configuration, the overall trend is consistent. This result supports the validity of the proposed approach for orientation discrimination based on relative signal variation. The observed voltage variation provides sufficient separation between different orientation states, indicating that the method can be used for reliable classification of segment alignment.

To further illustrate the applicability of the proposed method in a practical environment, a conceptual configuration of an automated inspection system is shown in Fig. 9. The system integrates a material handling mechanism, a sensing module, and a data processing unit. The Hall sensor signal is acquired and processed in real time, and the extracted feature is compared with predefined reference values. Based on this comparison, each magnet segment can be classified as correctly oriented or misaligned prior to the magnetization process. It should be noted that the system presented in Fig. 9 represents a conceptual framework rather than a fully implemented system.

These results demonstrate that the proposed method can identify orientation-dependent trends in unmagnetized anisotropic magnets and can be extended to automated inspection systems for detecting assembly errors before magnetization.

5. Conclusion

A pre-magnetization orientation identification method for anisotropic magnet segments has been proposed and experimentally evaluated. The method utilizes verification magnetic field and Hall sensor measurement to detect orientation-dependent variations in the magnetic response of unmagnetized magnets. An analytical model was developed to describe the relationship between the applied field, induced magnetization, and measured signal. The model provides a simplified framework for understanding the orientation-dependent behavior, focusing on the relative variation of the response rather than its absolute magnitude. Experimental results demonstrated that the peak Hall voltage varies monotonically with respect to the orientation angle, confirming the existence of a consistent orientation-dependent trend. Although the absolute values differ from the analytical prediction due to practical factors, the observed trend shows strong agreement with the proposed model. The results indicate that the proposed method enables reliable discrimination of magnet segment orientation prior to magnetization. In addition, a conceptual configuration of an automated inspection system was presented, demonstrating the potential applicability of the method to practical manufacturing environments.

The proposed approach can be used to detect misalignment in assembled magnet structures before the magnetization process, thereby improving assembly quality and reducing production defects. Future work will focus on repeated measurements, sensor position sensitivity, and sample-to-sample variation analysis for improved reliability evaluation, as well as refinement of the analytical model and implementation of a fully integrated inspection system for real-time industrial applications.

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