

# Foundational Study on Magnetic-Chain-Based Magnetic Flux Leakage Detection for High-Throughput Screening of Under-Magnetized Small Permanent Magnets

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**Abstract:** Small permanent magnets are indispensable functional components in smart electronic products, where the stability of magnetization directly influences actuation, positioning, sensing, acoustic output, and overall system reliability. In industrial production, however, the final magnetic performance of a small magnet is sensitive to raw-material fluctuations, local field nonuniformity, fixture tolerance, and process disturbance during magnetization. The dominant failure mode is insufficient magnetization intensity, which creates under-magnetized or “NG” parts. Existing commercial inspection equipment usually adopts a discrete strategy in which each magnet is measured independently. Although this approach offers high accuracy, its serial nature limits throughput and is increasingly incompatible with large-scale manufacturing. To support high-speed screening, this work develops a foundational study of magnetic-chain-based magnetic flux leakage (MFL) detection using Hall sensing and finite-element analysis. Rather than treating each magnet as an isolated inspection target, the method organizes multiple magnets into a chain and evaluates whether the leakage-field distribution along the chain can preserve sufficient contrast for reliable NG identification. A three-dimensional Ansys Maxwell model is established using NdFe<sub>36</sub> permanent magnets, with a single under-magnetized magnet embedded at the center of the chain. The study first constructs the batch-detection framework, then investigates the signal morphology obtained along vertical and horizontal sensing directions, and finally introduces direction-dependent threshold metrics for quantitative discrimination. For magnet lengths of 10, 8, and 6 mm, the vertical-direction thresholds are 40.35, 37.95, and 31.71, respectively, whereas the horizontal-direction thresholds are 27.99, 29.35, and 28.35. The results show that each magnet produces a quasi-N-shaped leakage signature in the vertical direction and a quasi-parabolic signature in the horizontal direction. More importantly, the vertical arrangement consistently provides stronger NG contrast and clearer waveform separation. This work therefore solves a key early-stage problem for magnetic-chain inspection: how to preserve both throughput and signal distinguishability in a batch-screening configuration. The study provides a physically interpretable detection metric, identifies the more favorable sensing direction, and offers direct guidance for subsequent equipment design, algorithm development, and extension toward more complex magnetic-chain inspection scenarios.

**Keywords:** Small permanent magnet; magnetic chain; magnetic flux leakage; Hall sensor; finite-element analysis; batch inspection.

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## 1. Introduction

Small permanent magnets are widely used in mobile electronics, acoustic modules, micro-actuators, positioning units, miniature motors, and other intelligent products. In these applications, magnetic performance is not a secondary material parameter; it is one of the decisive conditions that govern device output, switching sensitivity, motion repeatability, and long-term stability. A slight reduction in magnetization intensity may lead to insufficient actuation force, drift in magnetic alignment, unstable triggering thresholds, or product-to-product inconsistency. As miniaturized electronic systems continue to pursue higher integration and tighter tolerance windows, reliable magnet quality control becomes increasingly important [1,2].

In industrial magnetization processes, small magnets are not always magnetized to an identical state. Variations in raw-material batches, local field distribution, tooling precision, thermal conditions, and fixture positioning can all cause part-to-part deviations. The most common unacceptable condition is under-magnetization, namely, a magnet whose remanence is insufficient relative to design requirements. These NG parts are difficult to identify from appearance alone, but they can seriously degrade downstream product performance.

Consequently, post-magnetization magnetic inspection is a necessary step in production [2–5].

The current industrial mainstream is discrete inspection: each small magnet is measured independently by a dedicated station or probe. The strength of this strategy is precision, because each target is isolated and the measurement environment is relatively easy to control. Its weakness is speed. Serial inspection inevitably limits throughput, especially when the product line handles large numbers of small magnets in rapid succession. For high-volume smart-electronics manufacturing, this mismatch between precision and speed becomes a practical bottleneck. The challenge is therefore not merely to detect weak magnets, but to do so at production-compatible speed [1,3,5].

A magnetic-chain-based inspection configuration offers a promising route to high-throughput screening. Instead of measuring each small magnet independently, multiple magnets can be arranged as a chain and detected in a batch-like manner. However, once magnets are placed in a chain, their leakage fields couple spatially, and the measured signal becomes sensitive to chain geometry, sensor lift-off, sensing direction, and the position of the under-magnetized element. In other words, the gain in inspection efficiency introduces a new scientific and engineering problem: whether NG

information remains distinguishable after magnetic coupling and whether a stable decision metric can still be established. This is the key problem addressed in the present work.[4-6]

The goal of this paper is to build the foundational research story for magnetic-chain-based leakage-flux detection. The work does not begin from algorithmic post-processing; it begins from signal formation physics. Using finite-element analysis, we establish a magnetic-chain model and investigate how an under-magnetized magnet perturbs the leakage-field distribution within the chain. We then compare the vertical and horizontal sensing directions, reveal the different waveform morphologies produced by the same chain, and define direction-specific threshold metrics for NG discrimination. By doing so, the study answers an early but decisive question for batch screening equipment: what sensing direction and signal representation are more favorable for reliable detection. The outcome is not only a set of simulation curves, but a design logic that supports future hardware layout, threshold selection, and further expansion toward more comprehensive magnetic-chain inspection technology.[7-9]

## 2. Research Objective and Technical Story

The research background of this work can be summarized as a tension between quality assurance and manufacturing efficiency. On the one hand, every magnetized part must be checked because under-magnetization directly threatens product performance. On the other hand, conventional one-by-one inspection is too slow for high-throughput production. The central idea of this work is therefore to replace isolated inspection with magnetic-chain inspection while retaining sufficient detection fidelity. To realize this idea, several linked questions must be answered. First, how should the magnetic chain be represented in a simulation framework that matches the physical detection scenario? Second, when a single NG magnet is inserted into the chain, what kind of perturbation does it introduce into the leakage field? Third, which sensing direction provides better NG contrast? Fourth, how can the waveform difference be converted into a quantitative threshold for decision-making?

This paper answers these questions through a layered technical route. The first layer is model construction. A chain composed of NdFe36 magnets is established, including one under-magnetized element, a Hall-probe sensing point, and a surrounding air domain large enough to suppress boundary artifacts from the outer calculation region. The second layer is controlled comparison. Magnet length is varied while other factors remain fixed, allowing the sensitivity of chain-based inspection to be isolated and interpreted. The third layer is

signal interpretation. Vertical and horizontal sensing produce different waveform families, and these waveform differences are tied to the way edge fields, flux closure, and local gradients are projected onto the Hall sensor. The fourth layer is threshold design. Instead of describing results only qualitatively, the study defines threshold quantities that can be directly used in engineering decisions.[10-11]

In this sense, the paper solves more than one isolated problem. It solves the problem of turning a potentially ambiguous batch signal into a physically interpretable detection indicator. It solves the problem of identifying the more advantageous sensing direction for magnetic-chain inspection. It also solves the problem of linking simulation results to actionable design guidance. These are the foundations on which a practical high-speed inspection system can later be built.[12]

## 3. Finite-Element Model and Detection Strategy

### 3.1. Modeling framework

Leakage-flux detection is governed by electromagnetic field theory, and the present work uses Ansys Maxwell to perform three-dimensional finite-element simulation. The core purpose of the model is to reproduce the magnetic-field distribution created by a chain of small permanent magnets and to examine how the field is altered when one magnet exhibits insufficient remanence. The simulation route used in the source document includes solver selection, geometry construction, material definition, boundary treatment, mesh generation, solution setup, and post-processing. Although straightforward in workflow, this sequence is essential because the final discrimination ability depends strongly on a physically reasonable field model.[13]

The magnetic chain consists of multiple small NdFe36 magnets arranged continuously along one direction. “Good” magnets and “NG” magnets are distinguished through remanence: the good magnets are assigned a remanence of 1.1 T, whereas the NG magnet at the center of the chain is assigned a remanence of 0.9 T. In the length-comparison study presented here, all magnets share a width of 10 mm, a height of 10 mm, and a fillet radius of 2 mm, while their lengths are set to 10, 8, or 6 mm. The Hall probe is placed at a distance of 1.4 mm from the chain. This configuration is chosen to mimic an in-line inspection scenario in which the sensor samples leakage information from the side of the moving magnetic chain. Figure 1 presents the magnetic-chain detection concept extracted from the supplied document, and Figure 2 shows the material selection interface for NdFe36 used in the finite-element setup.[14]

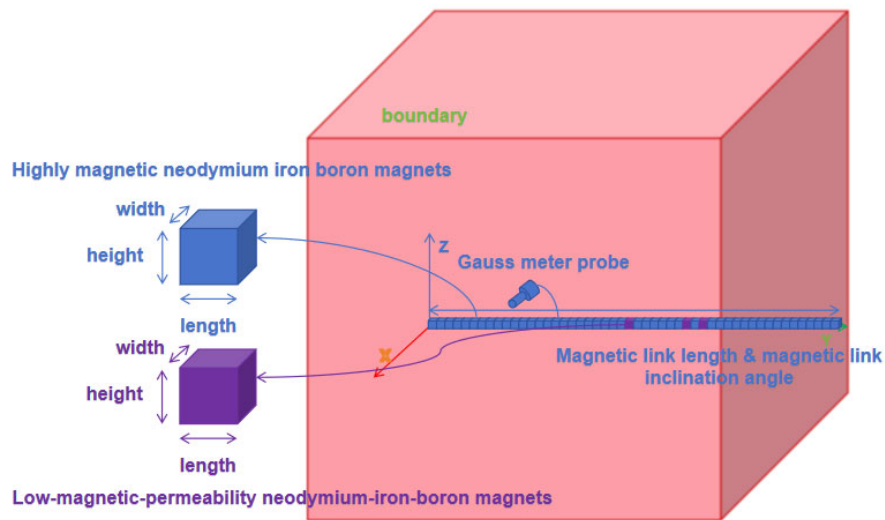


Figure 1. Magnetic flux leakage detection model based on magnetic chain

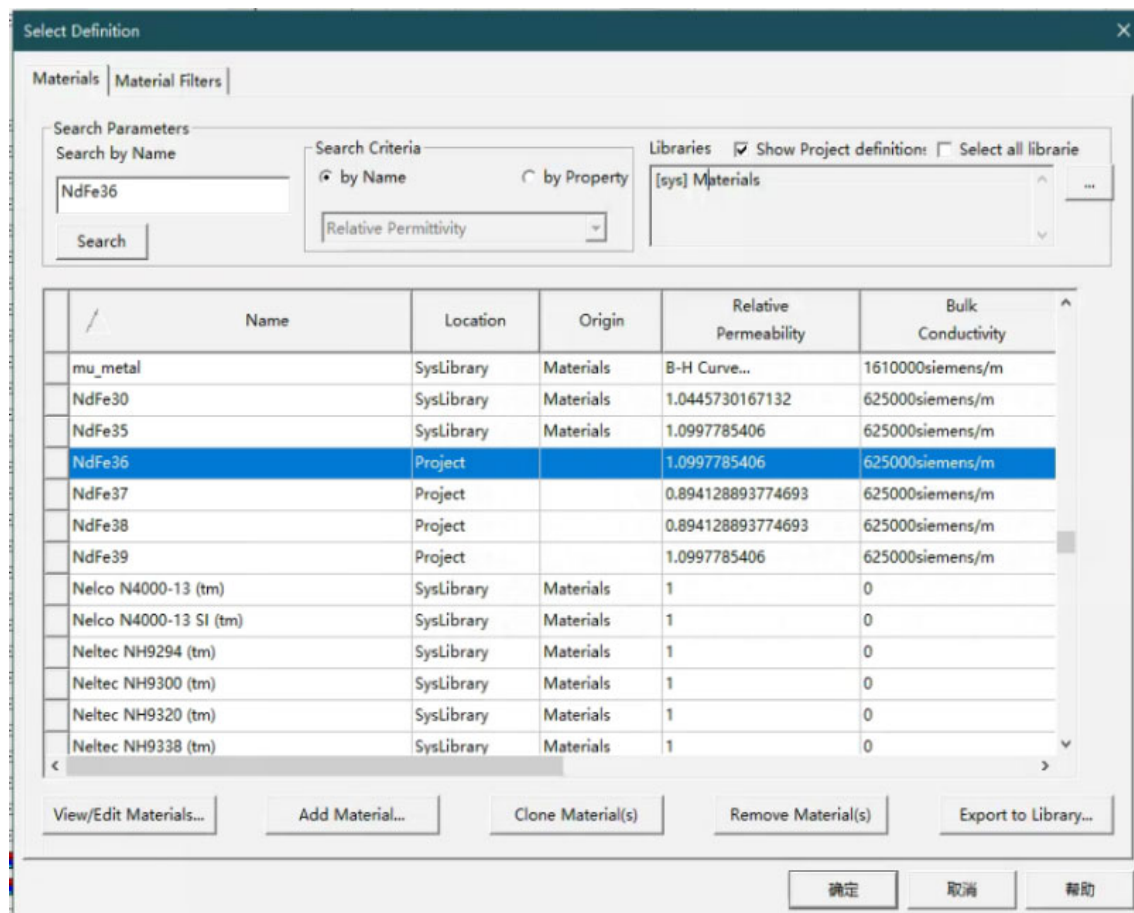


Figure 2. Material property definition

### 3.2. Simulation models and signal acquisition

To investigate how chain geometry influences the leakage signal, the study constructs three representative chains with different magnet lengths while keeping all other parameters fixed. The NG magnet is placed at the center in each case so that local signal distortion can be compared directly. Figure 3 collects the three simulation models corresponding to  $10 \times 10 \times 10$  mm,  $8 \times 10 \times 10$  mm, and  $6 \times 10 \times 10$  mm magnets.

Signal acquisition is performed along two measurement directions. In the vertical direction, the Hall probe samples the

component that reveals a repeated quasi-N-shaped pattern, with each magnet contributing one characteristic waveform unit. In the horizontal direction, the same chain produces a quasi-parabolic response per magnet. This directional dependence is not accidental; it reflects how the sensor projects the spatially closed leakage flux and edge-field gradient into a measurable scalar quantity. Because the chain contains one under-magnetized element, the local waveform near the center becomes distorted relative to the periodic pattern formed by the surrounding good magnets. The ability to detect this distortion is the basis of NG identification.

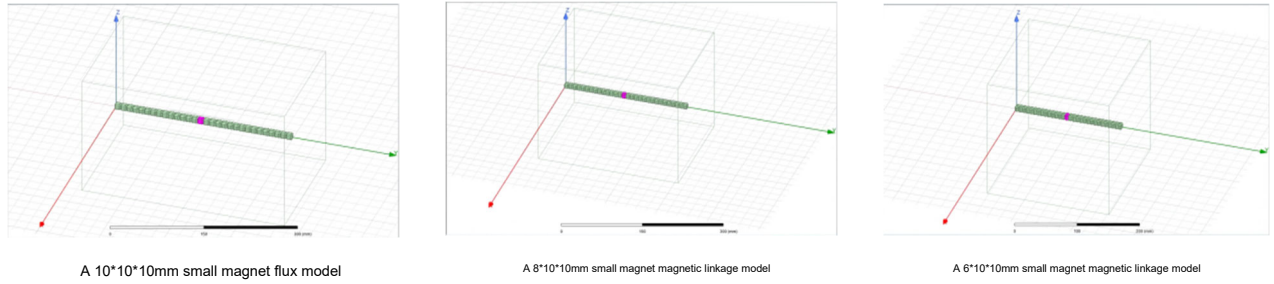


Figure 3. Simulation model.

### 3.3. Threshold definitions

A major contribution of the source study is that it does not stop at qualitative signal comparison. Instead, it introduces threshold quantities that translate waveform morphology into quantitative discrimination. For vertical sensing, the NG threshold is defined from the difference between the peak-to-peak amplitude of a good-magnet waveform and that of the NG waveform. This can be written as

$$T_v = (B_{\text{good,max}} - B_{\text{good,min}}) - (B_{\text{NG,max}} - B_{\text{NG,min}}).$$

For horizontal sensing, the NG waveform behaves differently, and the threshold is defined by the difference between the maximum value of the good-magnet waveform and that of the NG waveform:

$$T_h = B_{\text{good,max}} - B_{\text{NG,max}}.$$

These two definitions are consistent with the directional signal morphology observed in the simulations. More importantly, they provide a bridge from physical field distribution to engineering decision logic. Once a threshold is defined, the chain signal can be evaluated in a systematic way rather than through visual inspection alone.

## 4. Results and Discussion

### 4.1. Vertical-direction signal morphology

Figure 4 shows the leakage magnetic-induction waveform obtained along the vertical direction for three magnet lengths. The most striking feature is that each magnet corresponds to a quasi-N-shaped waveform segment. This repeated structure confirms that the magnetic chain preserves an ordered signal pattern even though multiple magnets are coupled together. The under-magnetized magnet breaks this periodicity locally, and its waveform amplitude is smaller than that of the surrounding good magnets. At the same time, the two neighboring good magnets are pulled upward, which further strengthens local contrast.[15]

This observation is important because it proves that magnetic-chain inspection does not erase NG information; rather, it redistributes that information in a spatially structured way. The NG magnet is not only weaker by itself, but also modifies the field around it. As magnet length increases, the peak-to-peak response of the good magnets becomes larger, while the NG waveform becomes relatively smaller. In practical terms, this means that vertical sensing benefits from longer magnets because the separation between normal and abnormal signatures becomes more pronounced. The signal is therefore easier to segment and interpret.

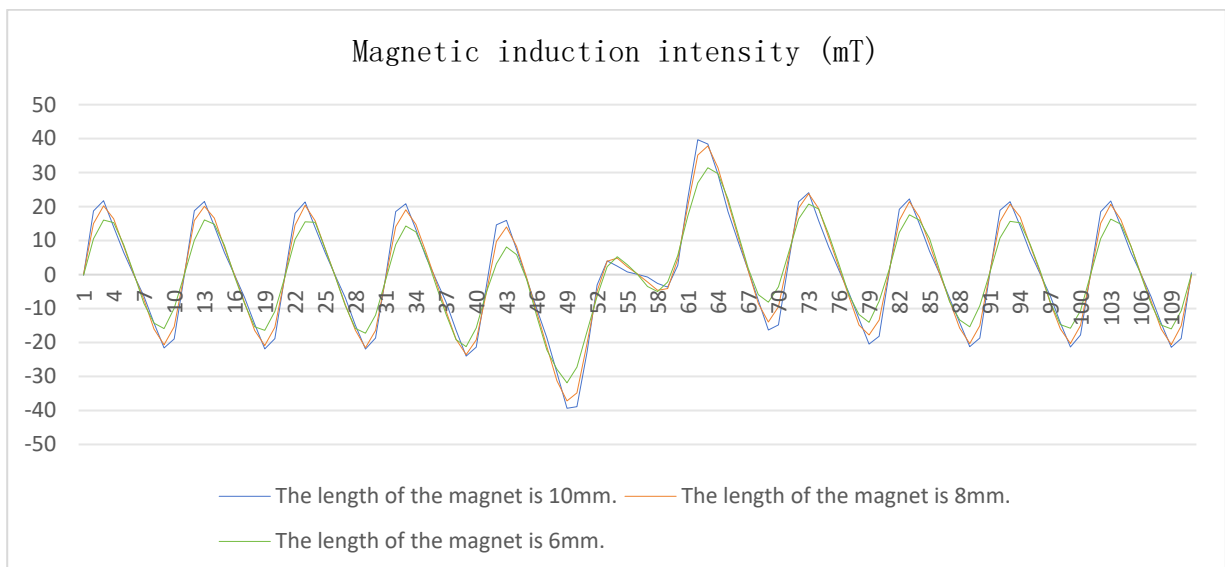
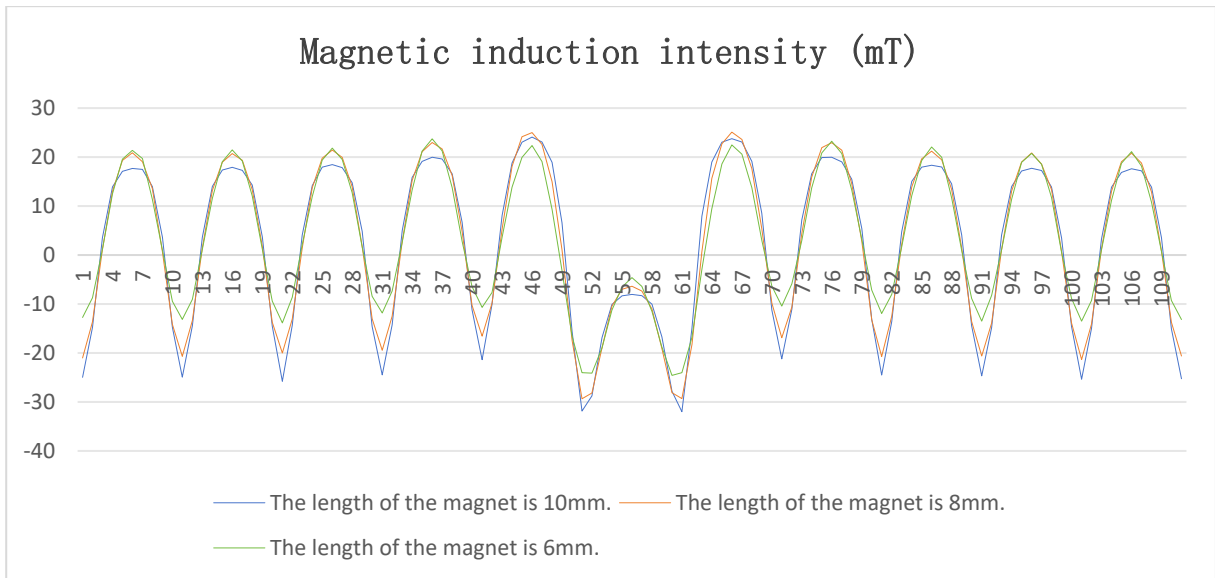


Figure 4. The waveform of the magnetic induction intensity of the magnetic flux leakage along the vertical direction of the magnetic flux chain

## 4.2. Horizontal-direction signal morphology

The horizontal-direction waveform in Figure 5 exhibits a different behavior. Instead of quasi-N-shaped segments, each magnet produces a quasi-parabolic response. The NG magnet still appears as a reduced-amplitude region, but the contrast between the NG magnet and the surrounding good magnets is less dramatic than in the vertical case. Moreover, the horizontal waveforms of good magnets are influenced much less by changes in magnet length.

This result explains why horizontal sensing is less favorable for magnetic-chain inspection. The horizontal projection captures a response that is smoother and more weakly differentiated in the region surrounding the NG magnet. Although the NG magnet remains detectable, the waveform family is less sensitive to the geometric enlargement that helps the vertical direction. Therefore, even when throughput is the primary motivation, choosing an unfavorable sensing direction can sacrifice the discrimination margin needed for reliable automatic screening.



**Figure 5.** The waveform of the magnetic induction intensity of the magnetic flux leakage along the horizontal direction of the magnetic flux chain

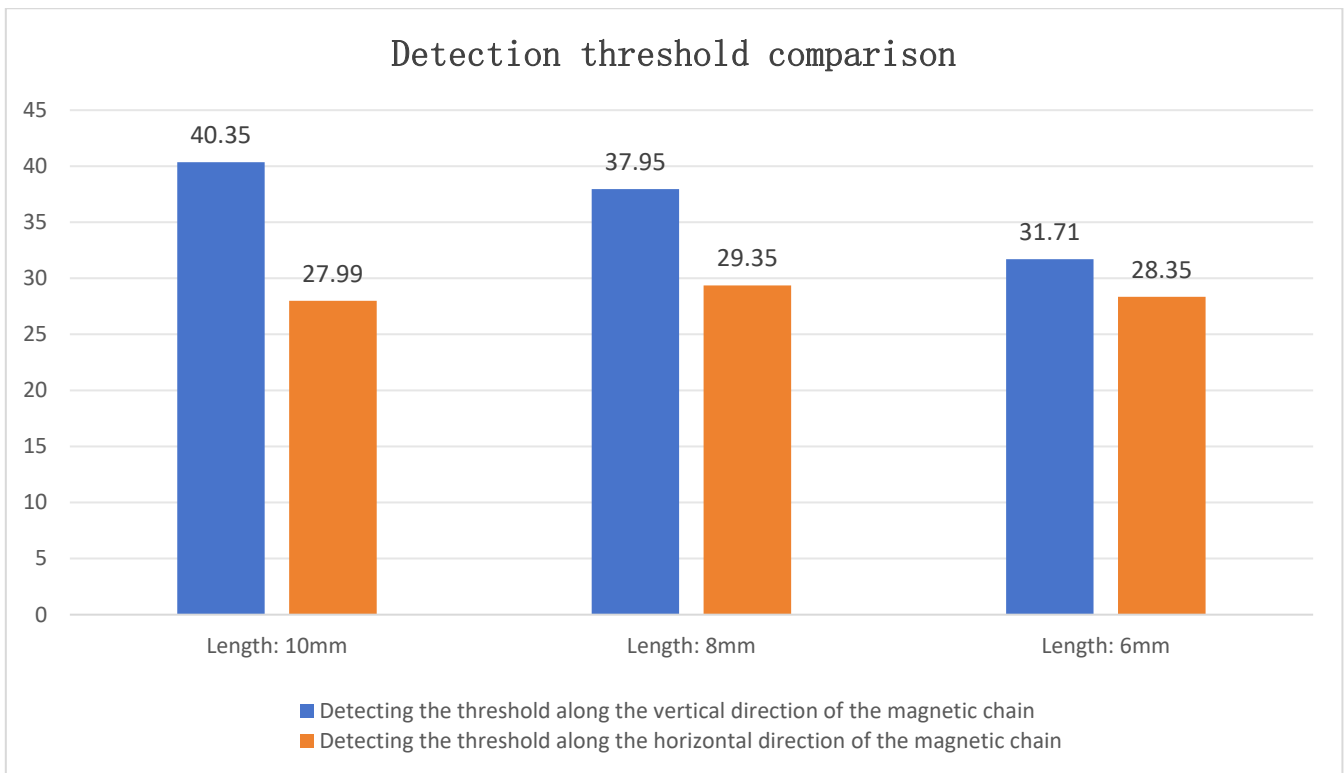
## 4.3. Quantitative threshold comparison

The threshold comparison extracted from the supplied document is summarized in Table 1 and visualized again in Figure 6. For magnet lengths of 10, 8, and 6 mm, the vertical-direction thresholds are 40.35, 37.95, and 31.71, respectively. The corresponding horizontal-direction thresholds are 27.99, 29.35, and 28.35. Two conclusions follow directly. First, the vertical direction provides a higher threshold than the horizontal direction for all investigated lengths. Second, the vertical threshold decreases noticeably as magnet length is reduced, whereas the horizontal threshold remains comparatively flat.

These trends have clear physical meaning. In vertical sensing, the field gradient associated with flux closure and edge leakage is exploited more effectively, so the NG-induced perturbation produces a stronger measurable difference. In horizontal sensing, the signal is more averaged and therefore less sensitive to the same perturbation. The data show that a magnetic-chain device should favor vertical-direction sensing when the goal is maximum NG discrimination. The data also indicate that longer magnets improve the chain's detection margin under the tested conditions. For the present study, the 10 mm configuration is therefore the most advantageous among the three cases investigated.

**Table 1.** Detection-threshold results

Magnet length	Vertical threshold	Horizontal threshold
10 mm	40.35	27.99
8 mm	37.95	29.35
6 mm	31.71	28.35



**Figure 6.** Thresholds detected along different directions of the magnetic chain

#### 4.4. What problem is solved?

From the perspective of industrial inspection, the study solves a foundational problem rather than a narrowly academic one. The problem is this: when magnets are inspected in a chain rather than individually, does the coupled leakage field still contain stable and usable information for identifying under-magnetized parts? The answer given here is yes, provided that the sensing direction and threshold design are chosen appropriately. The work demonstrates that batch-like chain inspection can retain distinguishable NG signatures. It further identifies a specific sensing strategy—vertical-direction detection—that consistently outperforms horizontal detection in the tested models.

This is not yet a full industrial machine, and it is not presented as such. What it provides is the physical basis needed to build one. The study turns a general production demand into a concrete detection route: use a magnetic chain to improve throughput, measure leakage flux with a Hall sensor, construct direction-dependent thresholds, and design the inspection geometry around the stronger vertical contrast. In this sense, the research story is coherent from beginning to end: it starts from a speed bottleneck in discrete inspection, identifies the physical challenge introduced by chain coupling, and ends with a viable signal-based solution for reliable screening.

### 5. Engineering Significance

The engineering significance of this work lies in its ability to provide actionable design rules for next-stage equipment development. First, the paper supports the feasibility of chain-based batch inspection for small magnets, which is important for manufacturing lines that cannot tolerate the throughput penalty of discrete one-by-one detection. Second, it establishes a quantitative basis for choosing sensor orientation. Instead of relying on intuition, equipment

designers can prioritize the vertical sensing direction because it produces larger discrimination thresholds under the tested conditions. Third, it shows that magnet geometry cannot be ignored in batch screening. Even in the simplified length study, the signal morphology and decision threshold vary systematically with magnet size. This suggests that future equipment should account for the actual product geometry rather than assuming universal signal templates.

The work is also meaningful from the standpoint of algorithm development. Threshold-based NG identification is much easier to automate when the underlying waveform has a stable structure, and the vertical quasi-N-shaped signal offers precisely this advantage. The study therefore provides not only field-distribution insight, but also a starting point for robust data processing, waveform segmentation, and real-time quality judgment. Finally, the methodology can be extended. Once the chain model and threshold framework are established, additional factors such as height, width, remanence level, multiple NG magnets, chain boundary effects, and tilt can be incorporated into a broader research program. The present paper should thus be understood as the foundational workload that makes such future expansion technically meaningful.

### 6. Conclusions

This paper develops a complete foundational study of magnetic-chain-based magnetic flux leakage detection for screening under-magnetized small permanent magnets. Motivated by the industrial limitation of conventional discrete inspection, the work asks whether a magnetic chain can preserve enough leakage-field contrast for reliable NG identification while offering a route toward higher throughput. A three-dimensional finite-element model using NdFe36 magnets and Hall sensing is established, and a central NG magnet is inserted to examine signal perturbation in a batch-like chain arrangement.

The results extracted from the supplied document show that the sensing direction is decisive. In the vertical direction, each magnet produces a quasi-N-shaped waveform and the NG magnet is distinguished by a reduced peak-to-peak response together with amplified neighboring signatures. In the horizontal direction, each magnet produces a quasi-parabolic waveform with weaker overall discrimination. Using direction-dependent threshold definitions, the study demonstrates that the vertical direction yields higher thresholds than the horizontal direction for all tested magnet lengths. Specifically, the vertical thresholds for 10, 8, and 6 mm magnets are 40.35, 37.95, and 31.71, compared with horizontal thresholds of 27.99, 29.35, and 28.35.

Therefore, the study solves the first key problem of magnetic-chain inspection: it confirms that NG information remains detectable in a coupled chain and identifies a sensing strategy that maximizes discrimination. The research provides a physically grounded threshold metric, validates the feasibility of chain-based screening, and supplies direct guidance for future equipment layout and automated quality-control design. In practical terms, it offers a credible path toward reconciling inspection accuracy with production efficiency in the magnetization quality control of small permanent magnets.

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