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Airgap-Dependent “Pole Eating” Effect in Magnetic Scales

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Summary: Magnetic scales and encoders are essential tools for precise measurement of linear displacement and angular rotation, especially in applications requiring long stroke lengths. However, material imperfections and errors in the magnetization process can result in inaccuracies within the magnetic zone patterns. This paper investigates the phenomenon of “pole eating”, where magnetic poles are partially diminished by neighboring poles at larger air gaps. A quantitative analysis of the impact of airgap variations on pole read-out accuracy is presented, focusing on three key error parameters: zone length variations, zone depth inconsistencies, and zone polarization irregularities. The findings provide insights into the tolerances necessary for reliable magnetic scale performance under varying air gap conditions, contributing to improved design and operational guidelines for magnetic measurement systems.

Keywords: magnetic encoder, scales, linear, rotary, pole errors

Background

Magnetic scales and encoders, linear and rotary, are vital for precise position and velocity measurements in industrial and scientific applications. Using Hall-effect or magnetoresistive sensors, they detect incremental or absolute magnetic patterns encoded on a scale [1].

Magnetic encoders outperform optical counterparts in robustness, tolerating dust, oil, and vibration, making them ideal for demanding environments like robotics, CNC machinery, and medical equipment.

Following [2], this study defines “zones” as magnetized material patterns and “poles” as the corresponding sensor signal patterns, with poles being the regions between consecutive zero crossings of the relevant field component.

Investigation of pole errors

Magnetic encoders are subject to various inaccuracies that can compromise their performance in precision applications [3]. Variations in the magnetic zones—specifically in their length, depth, and polarization (illustrated in Fig. 1)—often arise from material inhomogeneities, run-out errors, or imperfections during the magnetization process [4]. These variations manifest as distortions in the pole pattern of the measured signal, directly affecting both absolute and incremental position measurements.

This study demonstrates that these zone pattern variations influence the pole pattern in an airgap-dependent manner. This observation suggests that the exact configuration of the magnetic zones on the encoder scale is less critical than the resulting magnetic field measured above them. Notably, the magnetic field’s characteristics change with airgap distance, a phenomenon exemplified by the “pole eating” effect shown in Fig. 2. This insight provides a basis for reevaluating design and error mitigation strategies in magnetic encoder systems.

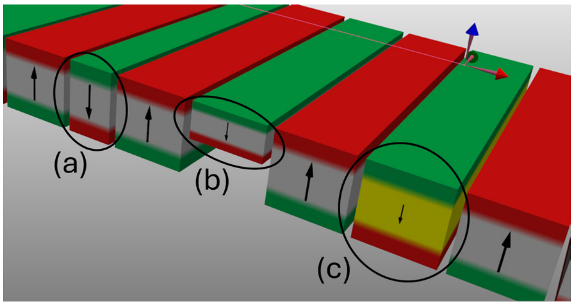

Fig. 1: Defects in zone patterns studied: (a) zone length variation, (b) zone depth variation, (c) zone polarization variation. A sensor above the scale detects the resulting field at a given airgap.

Results

To investigate the effects of pole length variation, we utilized Magpylib, an open-source library for analytical magnetic field calculations of permanent magnets [5]. Magnetic zones were modeled as idealized cuboid magnets, facilitating systematic parameter manipulation. The simulation parameters, representative of realistic linear and rotary encoder systems, are detailed in Tab. 1. The results are expressed as relative deviations, ensuring scaling invariance and minimizing dependence on the absolute parameter values of the system.

Starting from an ideal magnetic zone pattern, we introduced a single faulty zone and system-

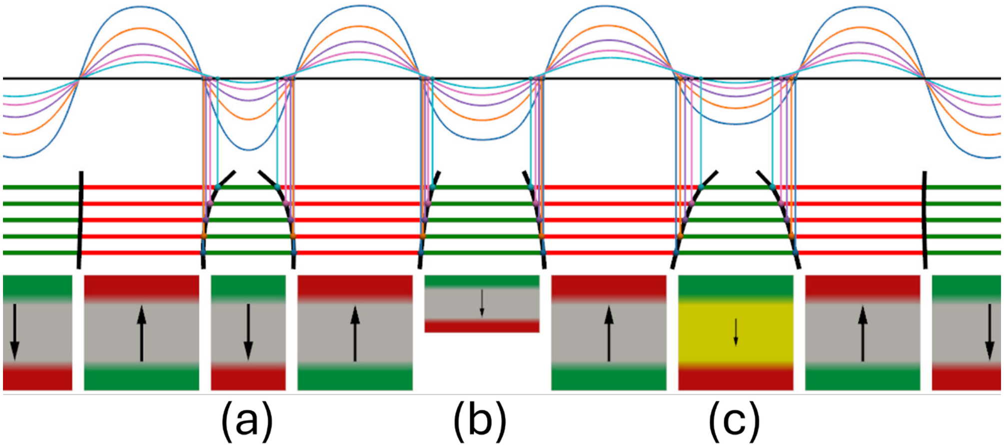

Fig. 2: Pole lengths measured above zone defects (Fig. 1a–c) at varying airgaps. Larger airgaps cause defect poles to be increasingly "eaten" by neighboring poles due to signal zero-crossing shifts (vertical field component).

Tab. 1: Input parameters for analytical simulations. Scaling invariance ensures results apply to systems of varying sizes.

zone length	$1\,\mathrm{mm}$
zone width	$5\,\mathrm{mm}$
zone depth	$0.5\,\mathrm{mm}$
magnetic polarization	$100\,\mathrm{mT}$ out-of-plane
read-out airgap	$\frac{1}{2}$ zone length = $0.5\,\mathrm{mm}$

atically varied three error types—zone length, zone depth, and zone polarization—by up to 10% of their original values. The deviations in pole length, expressed as percentages relative to the original pole lengths, were analyzed as a function of air gap variations. The results, summarized in Fig. 3, reveal how specific error types influence pole read-out under different air gap conditions.

Outlook

Our presented simulations provide initial insights into the sensitivity of pole length deviations to zone pattern imperfections. Current efforts are focused on experimental validation of these findings to establish a comprehensive understanding of error sources and their impact on signal quality in practical encoder systems.

References

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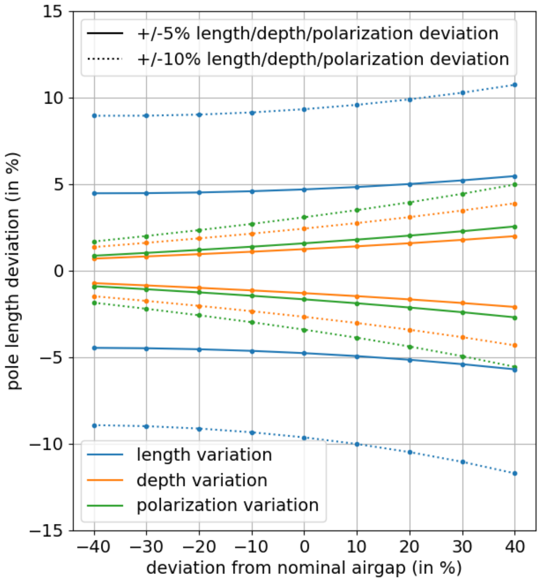

Fig. 3: Pole length deviations vs. airgap variations for different zone errors: length, depth, and polarization.

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