

Computational and Experimental Analysis of an Open Ring Specimen Measurement System for Characterizing Feebly Magnetic Powders

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This study presents a computational and experimental verification of a measurement system with slotted ring specimens for electromagnetically characterizing uncompressed, i.e., weak magnetic powders, which present promising materials for modern electric drives. Metrological challenges in characterizing feebly magnetic bulk materials, such as the stray flux compensation, are addressed. Therefore, a new signal model is analytically derived and validated using 3D finite element analysis, ensuring the accurate indirect determination of the specimen's averaged field quantities. A Monte Carlo analysis validates geometric parameters' sensitivity and reachable estimation accuracy compared to conventional setups using ring-shaped specimens. Additionally, the novel setup and the introduced signal model are verified with the help of 12 samples made of different iron powders.

Index Terms—magnetic materials, magnetic susceptibility, magnetization processes, powders

I. INTRODUCTION

IN modern electric drives, flux-guiding components are commonly manufactured from electrical steel sheets, soft magnetic composites (SMC), or, in rare applications, from amorphous iron [1]. Nevertheless, an increasing number of applications demand a wide speed and torque operating range, resulting in diverse electromagnetic operating points characterized by the flux density magnitude within the material and the magnetic field's frequency. In order to address these challenges, alternative non-solid materials such as uncompressed ferrous powders, ferrofluids, and iron-containing sponges offer new optimization opportunities due to their externally adaptable and, thus, variable macroscopic shapes. A varying shape in the magnetic circuit influences the air gap flux and, thus, the motor's characteristics depending on the operating point. However, the electromagnetic properties of these materials are generally unknown, especially at low material densities.

The electromagnetic properties of soft magnetic materials (SMMs), such as their magnetization curves, energetic behavior, and intrinsic or apparent electrical conductivity, are characterized by using ring samples [2]. This method provides several advantages compared to other approaches. The ring sample's geometry ensures a closed magnetic circuit including only one material and eliminates the need to account for discontinuous changes in the material's spatial distribution or demagnetizing fields based on macroscopic shape anisotropy during parameter estimation. Furthermore, this technique is simple to implement according to the low number of components, as illustrated in Fig. 1, and has been standardized in [3] for magnetic powders for frequencies up to 20 kHz.

However, in the case of powders, their low bulk density and, hence, a reduced amount of ferromagnetic material in the sample volume leads to a notable decrease in specimen's effective relative permeability towards a range of $\mu_r = [1, 100]$, cf. [4]. Thus, characterizing the sample's magnetization and loss behavior at high magnetic flux density magnitudes, e.g., 1.2 T, and magnetization frequencies reaching up to 100 Hz poses significant challenges. On the one hand, creating high

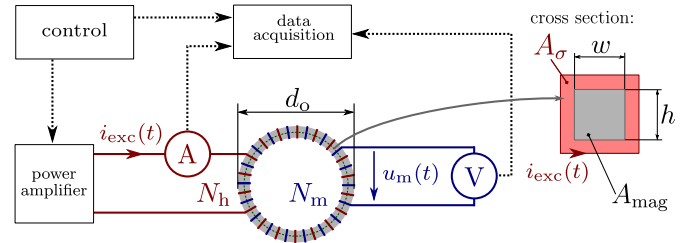


Fig. 1. Schematic of an experimental setup for characterizing ring-shaped specimen with indirect measurement of the electromagnetic field quantities.

flux densities in the sample cross-sectional area A_{mag} requires a very high number of turns N_h of the excitation system. On the other hand, the low effective permeability causes an improper ratio regarding the overall flux within the solenoid and the air flux, i.e., stray flux, linked in the cross-sectional area A_σ outside the specimen, making air flux compensation more complex.

For ring-shaped samples, the flux ratio between the stray flux Φ_σ and total flux Φ in the coil's cross-section with an area of A_c can be modeled as

$$\frac{\Phi_\sigma}{\Phi} = \frac{1}{1 + \mu_r \frac{A_{\text{mag}}}{A_c - A_{\text{mag}}}} = \frac{1}{1 + \mu_r \frac{A_{\text{mag}}}{A_\sigma}} \quad (1)$$

by assuming linear soft magnetic material with μ_r and a negligible stray flux outside the excitation coil. Corresponding trends for different A_σ are illustrated in Fig. 2. Typically used materials, e.g., electrical steels, exhibit a permeability $\mu_r \geq 1000$, resulting in an air flux content of less than 1 % even at $A_\sigma \gg A_{\text{mag}}$. Additionally, a small variable A_σ takes almost no effect on the absolute value of Φ_σ and, hence, typically does not influence the measurements. In contrast, for materials with low permeability, e.g., featuring $\mu_r < 10$, the stray flux can dominate the overall magnetic flux. i.e., $\Phi_\sigma/\Phi > 50\%$, and a fluctuation of μ_r or A_c leads to a drastic absolute change in Φ_σ and, thus, makes the measurement system stray flux-sensitive and the corresponding stray flux compensation is error-prone.

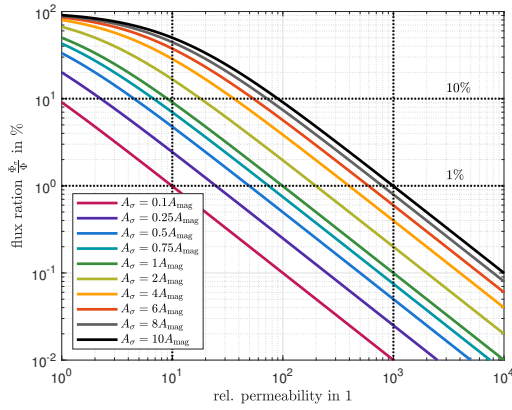


Fig. 2. Share of the stray flux Φ_σ in the total flux Φ within the excitation coil as a function of the permeability of the ferromagnetic material under test μ_r , its cross-sectional area A_{mag} and coil's area A_c .

Consequently, this work aims to enhance the existing measurement system for ring-shaped specimens to investigate feebly SMMs and compare their electromagnetic properties with conventional materials. The potential of ferrous powders in electric machines can only be assessed by examining the fundamental relationships, i.e., both the particle-level properties and the macroscopic electromagnetic behavior.

II. METHODOLOGY

Generally, the closed ring form requires each sample to be wound with a new individual coil system, i.e., an excitation and a sensing coil. As mentioned, a high variation in the effective stray flux is evident due to the low relative permeability of the uncompressed bulks. Additionally, sample preparation would be time-consuming, especially because of the high number of turns necessary to magnetize feebly magnetic materials. For the same reason, already known measurement concepts with a fixed coil system, e.g., the split-coil permeameter presented in [5] or [6], are unsuitable. Hence, a novel measurement system for ring-shaped specimens has been constructed as illustrated in Fig. 3 at the left, including two separate bobbins and a ring-shaped sample container with a slot. Thanks to the two-part coils, the toroidal excitation system can open up, forming a helix to insert different samples in their containers. The spatially fixed coil arrangement guarantees that the stray inductance and the flux linkage between the specimen and the excitation coil remain almost constant when the bobbin is closed. Accordingly, the stray flux compensation is accurately possible despite changing the samples.

As discussed, the introduced measurement setup uses an open, i.e., slotted, ring specimen. The sample can be threaded into the coil system by bending the ring-shaped sample to a helix. Therefore, the sample's dimensions must ensure the container is optimally fixed within the bobbins. Additionally, properly dimensioning the coil's winding number ensures that the amplifier's power is perfectly utilized while the defined electromagnetic operating point can be reached.

However, the sample modification, i.e., slitting the ring, has consequences, as the air gap and the resulting stray fields must be considered for indirect field quantity determination.



Fig. 3. Open ring measurement system for characterizing SMM powders featuring low material densities on the left side, and the 12 slotted sample containers filled with three different iron powders on the right side.

Therefore, an iteratively solvable signal model is derived from fundamental electrodynamics equations to compute the averaged field quantities in the specimen. Additional stray fields are formed by the separated halves of the excitation coil, making a numerical investigation of the winding systems' spatial arrangement necessary. Therefore, the whole setting and the introduced signal model are computationally evaluated using a 3D finite element analysis (FEA).

Finally, a numerical verification of the geometric parameter sensitivity using a Monte Carlo analysis and an experimental validation with 12 open ring powder samples, i.e., three different iron powders filled in four parallel samples, as illustrated in Fig. 3 on the right, is provided in the final paper.

III. OUTLOOK ON RESULTS

The conference contribution will treat the design and optimization process of the measurement system for characterizing open ring specimens with feebly magnetic properties, e.g., ferrous powders. Additionally, a new iterative signal model is derived and verified with FEA to determine the average field quantities indirectly. Finally, the measurement results gained with the system and its characterization procedure are tested on 12 open and one closed powder samples. First results reveal an improved electromagnetic parameter estimability and a good agreement with characterization results of the closed sample.

IV. ACKNOWLEDGMENT

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