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Characterization of Non-Highly Compressed Iron Powders in Ring Form for Application in the Field of Electrical Machines

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In this study, non-highly compressed iron powders in a ring-shaped sample container are characterized. This approach involves the dimensioning of a non-magnetic ring-shaped container to measure the magnetic properties of ferromagnetic powders with different bulk densities. Therefore, an optimization of the container's dimensions is presented. Finally, the precise data acquisition systems for determining the material's B-H characteristics and loss curves in relevant operating points are discussed and first measuring results for several distinct material densities are presented.

Keywords:
magnetic material characterization,
iron powder,
magnetization curve,
iron losses

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I Introduction

ferromagnetic materials such as laminated steel sheets made of silicon-iron (Si-Fe), nickel-iron (Ni-Fe), and cobalt-iron (Co-Fe) as well as soft magnetic composites (SMCs) and amorphous magnetic materials [1] are used.

Many studies have been conducted on analyzing the electromagnetic properties of ferromagnetics using an apparatus such as a vibrating sample magnetometer (VSM) [2,3]. However, despite its numerous advantages, utilizing a VSM entails certain limitations and concerns. One limitation is the requirement for relatively small sample sizes due to the spatial constraints of the instrument. In addition, no deformation, e.g., changing the sample's effective material density, of the sample is possible during the measurement.

Consequently, a simpler measuring system, i.e., the ring test method, according to the IEC standard [4], should be used. Setting up this method for powders involves numerous challenges related to selecting materials for the setup framework, e.g., the design of excitation systems, placing samples and sample holders, power electronics, measuring local field intensity, and controlling the system.

Several advantages are associated with characterizing magnetic materials in the form of a ring [5]. Firstly, the demagnetization field is zero, since the sample forms no magnetic poles. Secondly, the magnetic field strength and the rated change of the flux density can be indirectly estimated using simple equations. Nevertheless, a significant disadvantage is the non-homogeneous magnetic field and the very complex and time-consuming sample preparation time. Lastly, this initial study with a ring-shaped sample will allow the intrinsic properties of magnetic powders to be understood and the suitability of non-highly compressed powder materials for electromagnetic device application to be evaluated.

II Methodology

In this investigation, a method is introduced to characterize the magnetic properties of powders using a non-magnetic container in the shape of a ring to utilize the advantages of ring-shaped characterization, as schematically depicted in Figure 1. Typically, the material behavior in the desired B-field range is non-linear, and here it is non-linearly influenced by the fluctuating material density. A non-magnetic ring-shaped container is designed to hold the powders and the primary and secondary winding systems for controlling and measuring their current and induced voltage, respectively.

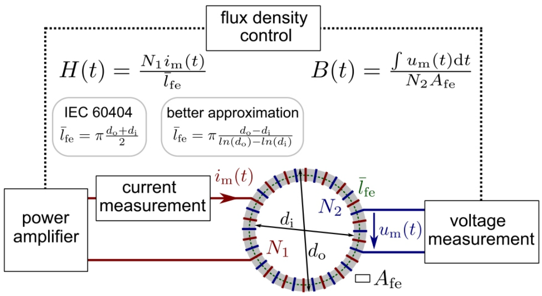

Figure 1: Experimental setup for characterizing soft magnetic materials with a ring-shaped specimen, taken from[6].

As candidate materials, pure iron powders can be mixed with insulators to create different distinct volume fractions regarding magnetic flux guidance for the samples, some of which are less than the bulk density, and some are more than the bulk density. To achieve this, varying amounts of iron powder should be compressed into the same sample holder. To achieve the goal of measuring field densities in the sample up to 1.2 T at 2 kHz and around 0.8T at approximately 10 kHz, the dimensions of the container need to be optimized. The selected values for the magnetic flux densities and frequencies correspond to the operating ranges of high-speed electric machines.

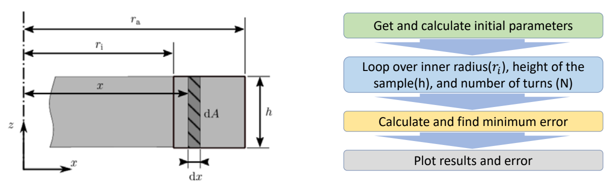

Figure 2: Ring-shaped specimen (left), optimization flowchart (right)

The key equations for calculating the magnetic flux density and inductance for the ring-shaped specimen (cross section side is shown in Figure 2 (left) are as follows:

$$B = \frac{\mu_0 \mu_r N I}{2\pi(r_a - r_i)} \ln\left(\frac{r_a}{r_i}\right) \tag{1}$$

$$L = \frac{\mu_0 \mu_r N^2 h}{2\pi} \ln\left(\frac{r_a}{r_i}\right) \quad , \tag{2}$$

where B is the magnetic flux density, μ_0 is the permeability in air, μ_r is the relative permeability, N is the number of turns for primary coil , I is the current, r_a is the outer radius, and r_i is the inner radius. The inductance and the resistance of the excitation coil determines the voltage drop of the coil which is limited by the amplifier. For optimization process, several assumptions are made. Firstly, it is assumed that the material is linear and that leakage flux and the effects of eddy currents on the resulting field are negligible. However, for the estimation of iron loss (R_{Fe}), the eddy current loss part should be considered. For loss estimation, a simple formula is used without considering the excess loss, thus it can be formulated as below:

$$R_{Fe} = K_h f B^n + K_{ec} f^2 B^2 \,, \quad 1.6 < n < 2 \tag{3}$$

where K_h is hysteresis coefficient, K_{ec} is the eddy current coefficient, and f is frequency. The ohmic resistance of the copper wire (R_{Cu}) can be calculated as follows:

$$R_{Cu} = \frac{N\left(2h + 2(r_a - r_i)\right)}{A_{cu} \sigma_{cu}} \quad , \tag{4}$$

where A_{cu} is the cross section of the wire, and σ_{cu} is the conductivity of the wire. The equivalent ohmic resistance (R_{eq}) of the coil includes both (3) , (4) , leading to a total power loss, where the according maximum total resistance R_{eq} is limited by the utilized amplifier:

$$R_{eq} = R_{Fe} + R_{Cu} \quad . \tag{5}$$

The impedance can finally calculated by using:

$$Z = \sqrt{{R_{eq}}^2 + \omega^2 L^2} \quad . \tag{6}$$

Here, ω is angular electric frequency. The maximum output voltage and current for the utilized Servowatt amplifier (DCP 780/60B) are 50 V and 15 A, respectively[7]. Based on these constraints and unknown parameters, an analysis can be conducted to identify potentially suitable configurations. A code is developed to find the optimal configuration, which is depicted as a flow chart in Figure 2 (right). The error is defined as the difference between the targeted values for flux densities and impedance with the calculated ones from the formula mentioned above (1,6) being as small as possible. The number of turns of the measuring (secondary) winding is dictated by the induced measuring voltage, which must fall within certain limits set by an amplifier and data acquisition box. With the existing data acquisition box (NI USB 6216), a voltage up to 10.4 Volts can be measured [8]. The measurement data, including the primary current and induced secondary voltage, are acquired through the mentioned data acquisition box, while applying anti-imaging and anti-aliasing filters. Real-time information is captured by the data acquisition system during the experimental process, ensuring accuracy and reliability in the characterization of magnetic properties. The anti-imaging filters smooth the signals generated by the output channel of the data acquisition box, and high-frequency content is removed by the anti-aliasing filter. Additionally, the experimental setup incorporates iterative learning control (ILC) to enhance the accuracy and efficiency of the characterization process [9]. The ILC algorithm is utilized to refine the control inputs applied to the experimental setup iteratively and to achieve the desired flux density waveform with a very low control error. The methodology allows to understand the magnetic properties of non-highly compressed iron powder in ring shapes. The results presented in the final paper will cover *B-H* characteristics at different frequencies, loss curves at various operating points relevant for electromagnetic device application, and the impact of iron powder density on all those properties.

III Conclusion and outlook

The expected results of this investigation revolve around obtaining comprehensive insights into the magnetic properties of non-highly compressed iron powders measured by samples of ring form, specifically targeting parameters essential for their application in electromagnetic devices. The results encompass *B-H* characteristics across various frequencies and loss curves corresponding to different operating point, preferably for sinusoidal flux density waveforms. The results will highlight the observed changes in hysteresis due to varying densities of iron powder, indicating a discernible shearing of the hysteresis curve, leading to a reduced non-linearity.

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