

# Improved Inductive Measurement System for Monitoring Electromagnetic Properties of Steel Sheets During Production

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## Summary:

This work improves on a previously investigated inductive measuring system to monitor electromagnetic properties of steel sheet during production. The goal was to increase the measuring range. In comparison to the earlier method, a reference system was used to subtract the influence of the primary field. A simulation using COMSOL Multiphysics® was used to validate the proposal. The results obtained by simulation showed that microstructural transformation may be more easily observed with a different sensor configuration and improved postprocessing.

**Keywords:** sheet rolling mill, magnetic analysis, alternating current characterization, eddy current sensor, inductive sensor, non-destructive testing

## Introduction

Steel is widely used in industries like electrical, mechanical, and civil engineering, each requiring specific properties. Electrical applications prioritize electromagnetic properties, while hardness, elasticity, and porosity are critical in others. These characteristics depend on steel's microstructure, making its monitoring essential for manufacturers. In-situ measurement techniques help assess if post-treatment is needed, allowing real-time corrections and reducing energy use compared to recycling faulty steel. This minimizes waste and supports greener production. [1]

## Background, Motivation and Objective

This paper presents an improved method of a measuring strategy investigated in a past publication [2], demonstrated in a simulation using COMSOL Multiphysics® and the Jiles-Atherton-Model. It was shown, that by evaluating the phase shift between an exciting magnetic field  $H$  and the induced voltage  $U_{ind}$  in a measurement coil, the composition of the steel microstructure could be reliably monitored, with a method suitable for high speed, high temperature and resistant to dirt. A challenge remaining is the superposition of the weak measurement signal and the primary field reducing resolution and therefore informative value on the composition. This study examines the magnitude of the primary field's influence on measurement outcomes and assesses how subtracting an empty

measurement without a steel sheet affects this influence. Such a subtraction of the primary field can be achieved by a thoughtful coil configuration as in [3] or by a reference system as in [4].

## Approach

The measurement method used in this work is based on the evaluation of the phase shift between H-field and B-field. As shown in [2], this phase shift is influenced by the coercivity  $H_c$  of a hysteresis curve. The current in the field coil serves as an indirect measure of the H-field. The B-field is determined on the basis of the voltage induced  $U_{ind}$  in the measuring coil.

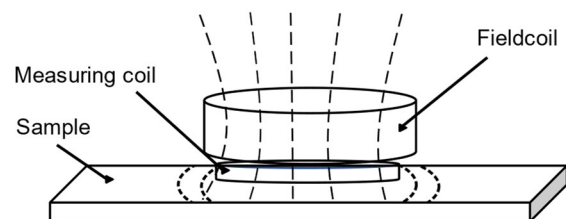


Figure 1: scheme of the simulation model

A flat measurement coil is positioned at a minimum distance of 7.5 mm above a sheet sample. Directly above the measurement coil, a second flat coil, designated as the field coil, is placed. The field coil is driven by a sinusoidal alternating current with an amplitude of 1,5 A. In the simulation, two hysteresis curves with different  $H_c$  were simulated in which small changes in  $H_c$  are generated by the pinning losses parameter. The two different hysteresis curves serve as model for

different microstructure compositions. However, since in this case the induced voltage  $U_{\text{ind}}$  is influenced by the sum of the primary generated field  $B_p$  and the opposing field generated by the eddy current  $B_{\text{eddy}}$ , the following equation is obtained:

$$\begin{aligned} B_{\text{res}} &= B_p + B_{\text{eddy}} \\ \rightarrow \hat{B}_{\text{res}} \sin(\omega t + \varphi_{\text{res}}) \\ &= \hat{B}_p \sin(\omega t + \varphi_p) + \hat{B}_{\text{eddy}} \sin(\omega t + \varphi_{\text{eddy}}) \quad (1) \end{aligned}$$

The following equation for the resulting phase position results from the sine addition theorem and transformations:

$$\varphi_{\text{res}} = \text{atan} \frac{\hat{B}_p \sin \varphi_p + \hat{B}_{\text{eddy}} \sin \varphi_{\text{eddy}}}{\hat{B}_p \cos \varphi_p + \hat{B}_{\text{eddy}} \cos \varphi_{\text{eddy}}} \quad (2)$$

As the primary field can be used as a reference phase, it can be summarized as shown in Eq. 3

$$\varphi_{\text{res}} = \text{atan} \frac{\hat{B}_{\text{eddy}} \sin \varphi_{\text{eddy}}}{\hat{B}_p + \hat{B}_{\text{eddy}} \cos \varphi_{\text{eddy}}} \quad (3)$$

This demonstrates that the resulting phase position is always compressed by the amplitude of the primary field. By subtracting an induced voltage from a reference measurement, the primary field can be suppressed and the measurable phase differences can be increased. For this purpose, the simulation from [2] was repeated and another one was done with a sample of air. The phase differences  $\varphi$  between the induced voltages and the exciting current were then observed.

## Results

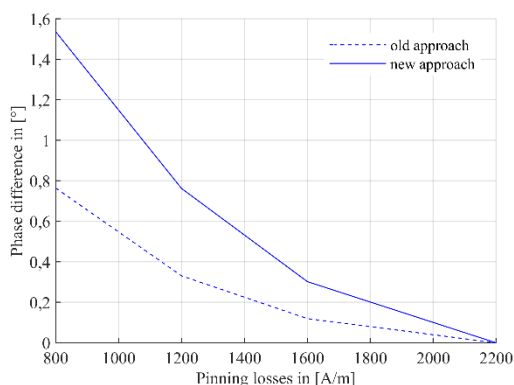


Figure 2: Phase difference over pinning losses for old and new approach relative to pinning losses at 2200 A/m

The results in Fig. 2 show an increase of the differences between all phase differences of the first hysteresis curve. For the first hysteresis curve, the difference increases by a multiple. For the second, at least twice as much. And the distance between the two curves increases by a factor of 5, as compared to the previous method (Tab. 1).

Tab. 1: Phase difference  $\Delta\varphi$  observed in simulation with (New) and without (Old) subtraction of a reference.

	Old	New
$\Delta\varphi_{\text{max}}$ curve 1	0.0155	0.4781
$\Delta\varphi_{\text{max}}$ curve 2	0.7639	1.5355
$\Delta\varphi$ curves 1-2	-1.0679	-5.3351

## Discussion

A substitute value  $\varphi_{\text{res}}$  for the coercivity  $H_c$  is measured by using inductive sensors, using a method that is directly suitable for in-situ applications. This method enables the value to be recorded precisely under real conditions without having to change the system or the measuring environment. The use of a reference system for the subtraction of the primary field leads to a considerable extension of the measuring range and thus offers higher accuracy and reliability compared to the previous method. For an application, the subtraction of the sample needs to happen in-situ, as a measurement with and without sample may not be possible to do simultaneously. With a thoughtful positioning form an extra set of coils it should be possible to measure the primary field without the field from the eddy current. [3] This paper show that it is beneficial to subtract the field generated by the primary coil from the field generated by the eddy current.

## References

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