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LORENTZ FORCE EDDY CURRENT TESTING: VALIDATION OF NUMERICAL RESULTS

ABSTRACT *The paper at hand reports investigations regarding the characterization of an a electrically conducting solid state specimen with a new non-destructive measurement technique for the detection of subsurface defects. On the one hand it is necessary to characterize a specimen without defects in order to detect defects, on the other hand we show the validation of the analytical and numerical models that are used to simulate the application.*

Keywords: *solid state specimens, non-destructive measurement, defects, analytical models, numerical models, simulation, finite element method.*

1. MOTIVATION

Inspecting materials and products without destroying test samples is a lucrative field in engineering since it saves costs and ensures a certain quality of the inspected good. The classical methods of non-destructive inspection,

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e.g. ultrasonic, radiography, eddy current testing or liquid dye penetrants, that are widely spread in metal production are limited in depth, resolution or require special conditions on the testing environment such as liquids that couple the test signal into the specimen.

In order to improve some of these limitations Lorentz Force Eddy Current Testing (LET) has been invented. The main goal in using LET is to overcome the current limit of inspection depth and improve the detection of deep laying defects within electrically conducting materials. The measurement technique bases on Ohm's law of induction for moving conductors

$$\vec{j} = \sigma\left(\vec{E} + \vec{v} \times \vec{B}\right) \tag{1}$$

where $\vec{j}$ is the induced eddy current density, σ the electrical conductivity of the specimen, $\vec{E}$ the external electrical field and $\vec{v}$ the relative velocity between the specimen and the source of the magnetic field $\vec{B}_0$. Finally the Lorentz force $\vec{F}$ opposing the specimens movement can be calculated by

$$\vec{F} = \iiint_{(V)} \vec{j} \times \vec{B}\, dV \tag{2}$$

Note that according to Newton's third axiom "action = reaction" the generated Lorentz force is not only acting on the moving specimen but on the source of the magnetic field as well. This force can be measured using commercial force sensors. Since the Lorentz force is constant for constant velocity and conductivity the idea of LET is to detect defects from resulting changes in the Lorentz force profile.

To detect changes in the Lorentz force profile precise knowledge about the behaviour of a solid state specimen without defect is necessary. Naturally it is not possible to provide experimental data for every set of parameters. That is why we want emphasize on the validation of our models used in this paper.

In the following sections we present very briefly the used models and compare the experimental results with the numerical solutions.

2. ANALYTICAL MODEL

The analytical model is based on [4], which describes how to calculate the force on a current coil moving over a conducting sheet of arbitrary thickness with the use of a modified Fourier transform approach. The force is directly described in terms of the Fourier transform of the current in a coil. The permanent magnet (PM) is substituted by a set of parallel polygonal current loops (see Fig. 1). Results are presented in Sect. 5.

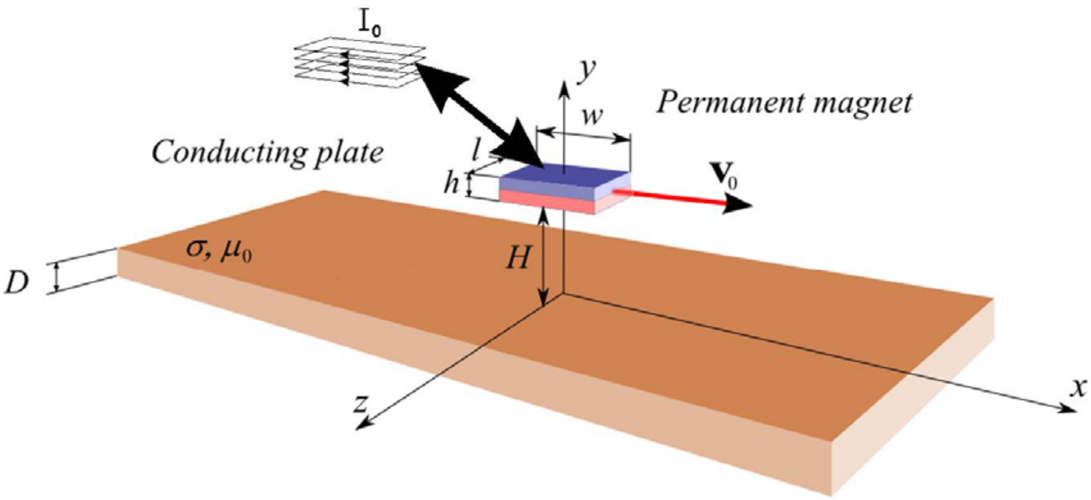


Fig. 1. Substitution of a permanent magnet (PM) by a set of four current coils, where *D* is thickness of the conducting sheet, *σ* its conductivity and μ0 the absolute permeability, *H* the lift-off distance, *h*, *l* and *w* the dimensions of the PM respectively the coil, *v* its velocity and $I_0 = \frac{B_r h}{\mu_0 N}$ the current in every loop with B_r as the remanent inductance of the PM and *N* the number of loops

3. NUMERICAL MODEL

The main task for the characterization of the specimen without defect in terms of Lorentz force has been the calculation of the drag F_x and lift force F_z components. Therefore a quasi-static 3D model has been applied in Comsol Multiphysics. The edges have been considered to be far away from the region of interest where the specimen is in the vicinity of the PM. As a consequence the specimen appears to be infinite long and it is possible to determine both force components by integration over the volume according to Eq. (2). To calculate the characteristic Lorentz force profile (see Fig. 2) a 3D transient solution is necessary.

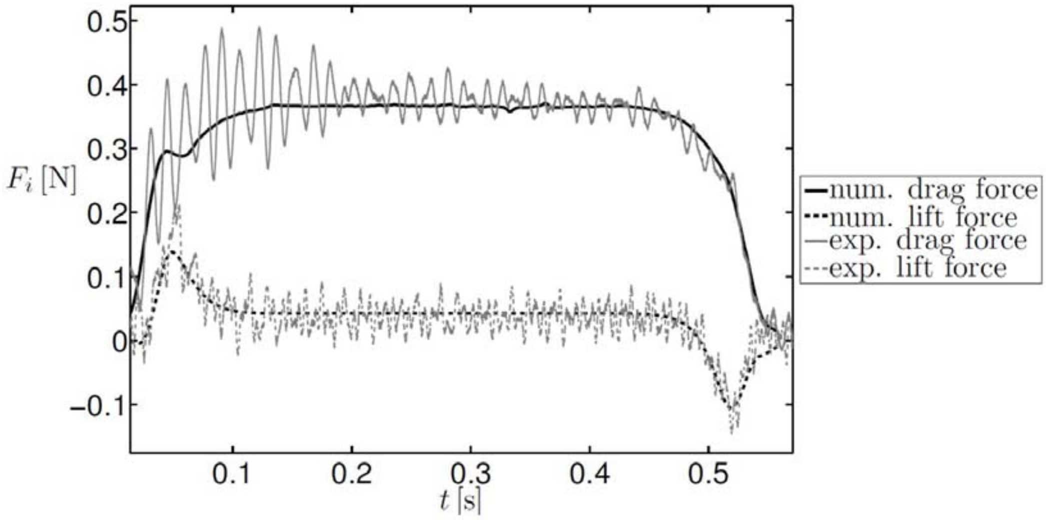


Fig. 2. Raw signal and numerically (transient) obtained characteristical profile at v = 500~mm/s and δz = 3 mm

4. EXPERIMENTAL SETUP

Obtained analytical and numerical results have to be validated to ensure the legality of the used models. The experimental setup has been built according to Fig. 3.

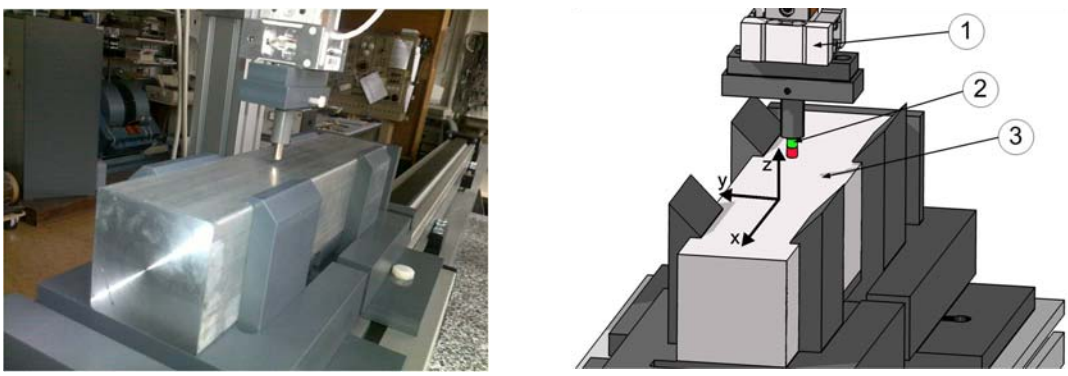


Fig. 3. Basic experimental setup comprising a (1) force sensor, (2) permanent magnet and (3) specimen (a) Photography (b) Sketch

The crucial parameters for the measurement of Lorentz force are the relative velocity and the lift-off distance. Therefore a linear belt-driven drive with a high constancy in velocity and an accurate positioning system for the magnet are used. Since the linear movement of the specimen is easier to handle we decided to fix the magnet and the force sensor. The specimen is moved by a belt driven linear drive manufactured by ”Jenaer Antriebstechnik GmbH”. Due to the high range of velocities it is possible to investigate effects of higher magnetic Reynolds number R_m which results in a non-linear dependency between drag force and velocity. The linear drive is carrying a sledge on which the specimen is mounted.

The specimens used are a solid bar made of Al-alloy, metallic sheets made of the same material and a solid bar made of copper. All specimens have the same overall dimensions, i.e. 50 × 50 × 250 mm.

The magnetic field is decaying fast in space. Since the generated Lorentz force is dependent on the field strength acting on the specimen, a precise positioning device is needed to place the PM above the specimen. Therefore, we use an electrically controlled microscope positioning table in y-z-direction, i.e. a planar drive. The table is turned by 90° to move the magnet relatively to the specimen. To overcome the gravitational force of the force measurement device and a rod a gravity compensation using a mechanical spring has been considered. The relevant system parameters of the drives are listed in Tab. 1.

TABLE 1
Parameters for used drives

Parameter	Linear drive	Y-Z-table
Type	belt driven	electrical step drives
Maximum velocity	3.75 m/s	40 mm/s
Accuracy	100 µm	30 nm
Range of motion	3m	45 × 45 mm

The alignment of the PM relative to the bar is done very accurately using a force feedback procedure [5]. This guarantees a reproducibility of the position within a few micrometers.

5. VALIDATION

The main motivation for all following investigations is the detection and namely the identification and localization of defects deep inside an electrically conducting material. To make sure that an artifact in the measured signal is the effect of a defect we first characterize a solid state body specimen without any defect. Second we approximate the solid specimen by a package of metallic sheets made of the same material to have the chance to vary a defect in size, form and depth which is not presented in this work.

5.1. Lorentz Force vs. Time

The data acquisition unit of the force signal is a PXI real-time system by "National Instruments". The maximum sampling frequency is limited to f_{sample} = 10 kHz by the amplifier of the strain gauge signal. The PXI unit can be adjusted to the necessary sampling frequency that is needed. In order to generate the maximum number of data points on the specimen within the vicinity of the PM, we use the maximum available frequency of f_{sample} = 10 kHz.

Due to the given conditions of the laboratory the signal-to-noise-ratio is rather poor. So the necessity of appropriate filter techniques arises. The raw signal has been investigated using Fourier transformation and wavelet transformation as well. The main difference between Fourier and wavelet transformation is the resolution of the signal in time. Wavelet transformation gives the user the information which frequency components are active at a certain time whereas Fourier transformation states a periodic signal and does not take changes in time into account (see Fig. 4).

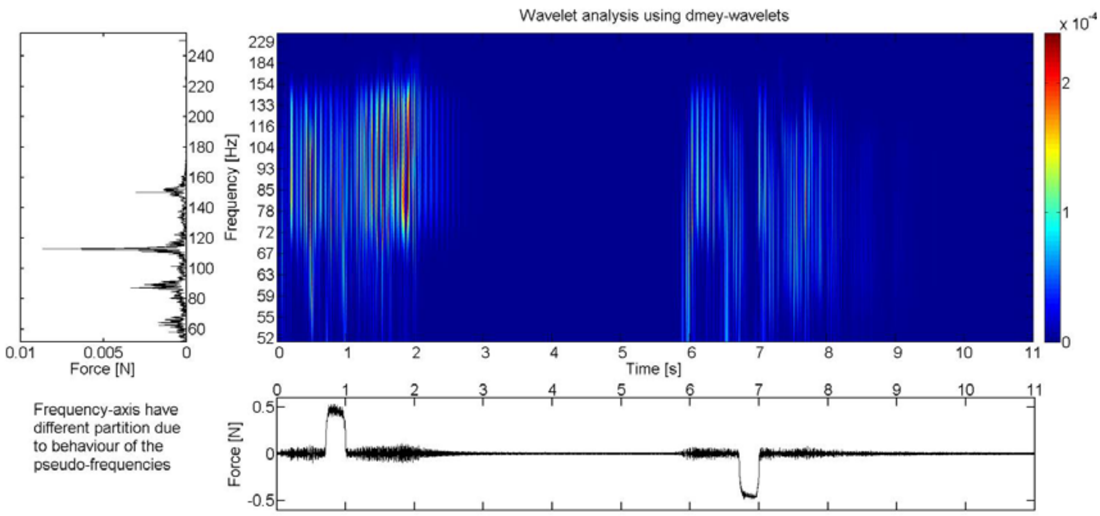


Fig. 4. Raw signal at *v* = 900 mm/s (going forth and back) and *δz* = 3 mm (bottom), its wavelet decomposition (middle) and Fourier transformation (left)

The used filter has to follow the signal relatively fast since for high velocities only a few data points are available. The application of classical mean value generating filters is not possible because they are restricted to a thin working range. To avoid setting up filters for every measurement velocity the filters according to Tab. 2 have been applied.

This leads to a smooth graph for low and medium velocities (0.1 . . . 1.2 ms). For higher velocities the oscillations are not filtered out well anymore, because there are not enough data points available in the region of interest. In order to compare the obtained velocity with the numerical one, we compare the measured mean value in the middle of the specimen. This helps us to correct any misalignment and mounting declination.

TABLE 2
Applied filters

Effect	Filter	Frq. [Hz]	Sampling frq. [Hz]
Foundations frequency	Notch filter	10.9	44
Power frequency	Notch filter	50	200
Mechanical mounting	Band-stop filter	60 . . . 90	300
White noise	Dmey-wavelet filter	≈50 . . . 230	*continuous*

The presented measurements and calculations have been studied on the symmetry line of the specimen along the movement direction. So there is no lateral force F_y expected. It can serve as a quality parameter for the alignment.

5.2. Lorentz Force vs. Velocity

As shown in [2] and [3] Lorentz force is linearly dependent on velocity for low magnetic Reynolds numbers R_m.

$$R_m = \mu \sigma v b \tag{3}$$

where μ is the magnetic permeability and b is the characteristic length scale, i.e. the width of the specimen. Since R_m is dependent on conductivity and velocity the linearity is not given any more for copper in regions where Al-alloy is still linear in drag force F_x and quadratic in lift force F_z (see Fig. 5).

a)

b)

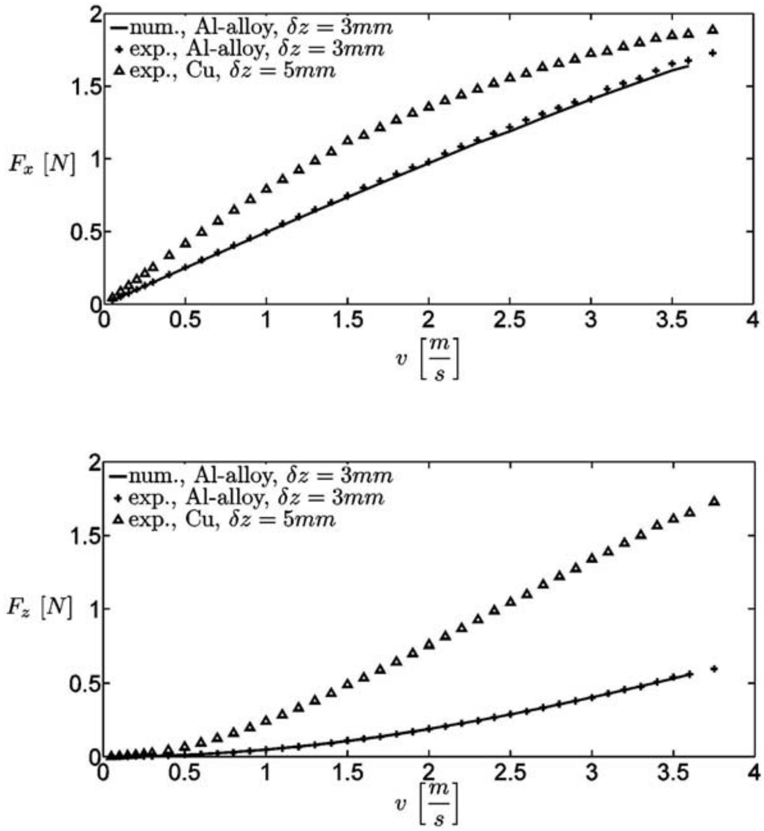


Fig. 5. Dependency of force on velocity for Al-alloy and Cu, lift-off distance δz = 3mm and 5 mm respectively (a) Drag force (b) Lift force

5.3. Lorentz Force vs. Lift-Off Distance

The knowledge of the dependency of Lorentz force on the measurement velocity is the first step to determine an optimal measurement velocity. The velocity is one of several parameters that have to be adjusted before the measurement. Another one is the lift-off distance δz which is the shortest distance between the magnet surface and the specimen surface.

Figure 6 shows the Lorentz force with respect to lift-off distance. It is obvious that the behaviour cannot be described by using a single power law. The magnetic field distribution of a cylindrical PM differs from a magnetic dipole in that the field decays with δz3 [6]. The decay of the Lorentz force is leading to a change in sensitivity of the measured force in respect to the lift-off distance. The conclusion one draws from this fact is that for every application another working point is optimal. Having in mind that defect detection is the main goal one would suggest to stick to an intermediate lift-off distance to avoid strong oscillations due to surface quality.

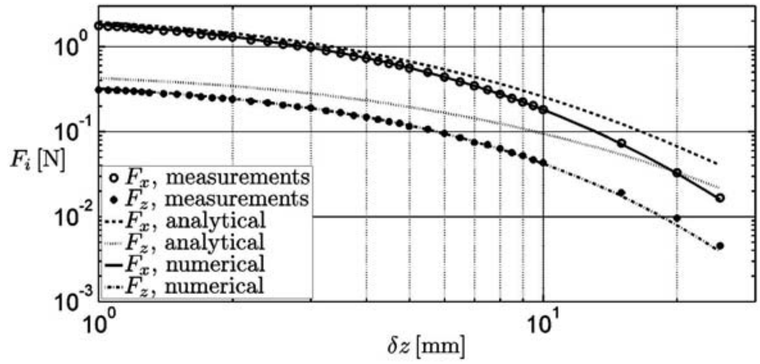
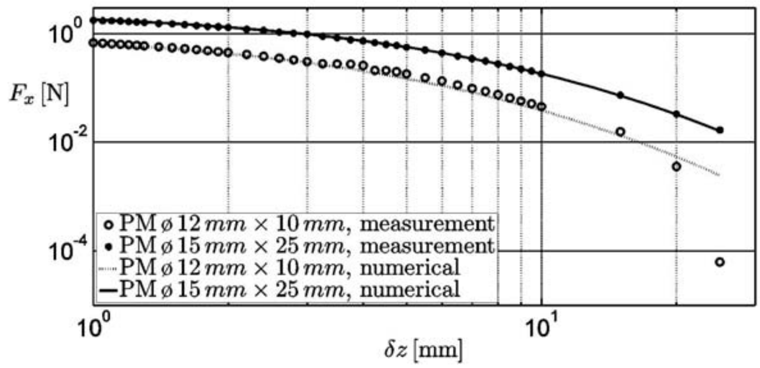


Fig. 6. Comparison between analytically, numerically and experimentally obtained force components with respect to lift-off distance δz for a cylindrical permanent magnet ϕ 15 × 25 mm

Another conclusion one draws from Fig. 6 is that the analytical model is only valid for small lift-off distances whereas the numerical model is valid for a wide range of setup parameters. To prove the validity of the numerical model for different PM shapes one finds Fig. 7.

a)



b)

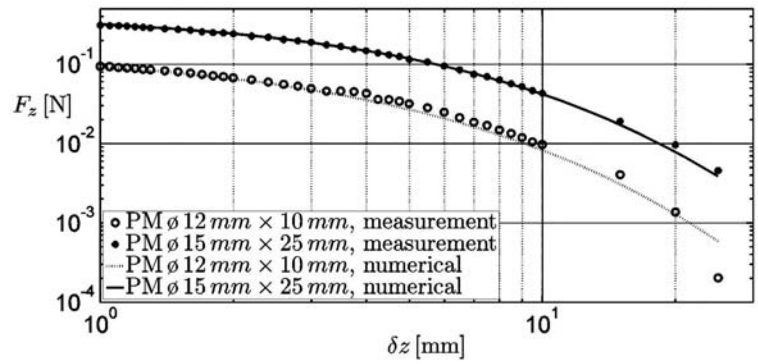


Fig. 7. Dependency of force on lift-off distance for Al-alloy and magnet size, where *v* = 2 ms (a) Drag force (b) Lift force

The numerical solution is close to the experimental results. For very high distances the high discrepancy is a result of the uncertainty of measurement due to the tiny forces.

6. CONCLUSION

The applied analytical model and the 3D quasi-static numerical model have been validated using experimental data. The analytical model is valid only for small lift-off distances, i.e. the distance between the specimen and the magnet is small compared with the distance between the magnet and the edges of the specimen. We determined the dependency of Lorentz force with respect to velocity and have shown that for high magnetic Reynolds numbers R_m the dependency is nonlinear. Nevertheless the numerically obtained prediction of the Lorentz force is very accurate. It turns out that quasi-static numerical calculations provide a good prediction of the behaviour of the LET-measurement without defect whereas the analytical solution is limited in accuracy by the assumption of the infinite sheet. The case with artificial defects will be discussed in future work.

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TESTOWANIE WIROPRĄDOWE W OPARCIU O POMIAR SIŁY LORENTZA

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STRESZCZENIE *Artykuł opisuje badania charakteryzujące elektrycznie przewodzącą próbkę w stanie stałym przy użyciu nowej nieniszczącej techniki pomiarowej w celu detekcji defektów podpowierzchniowych.*