Motion induced eddy current testing system based on rotating magnets

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Abstract

Non-destructive testing, especially of safety relevant components plays an increasing role in modern times. A portable version of a motion induced eddy current testing (MECT) system is introduced in this study. Measurements with different specimen and different defects are performed to prove the system’s ability for defect detection in electrically conducting materials. Additional studies on the alignment angle and the rotational velocity help to understand the functional principle of the portable MECT system.

1. Introduction

In modern times the requirements on technical components and their materials increase rapidly. Many parts are optimized to carry high loads with a minimum of material input. For example, the design of components for transport applications in airplanes or cars approaches the limits of what is technically feasible. Due to the increasing complexity of technical components, they should be tested in a non-destructive way already during the production process. Especially safety relevant components should be tested without destroying them in regular inspections to ensure the quality requirements before and during usage.

In the field of non-destructive testing (NDT) exist several techniques for material testing such as ultrasonic, radiographic or electromagnetic methods. An overview about the physical principles is given in (1).

In the framework of electromagnetic testing, motion induced eddy current testing (MECT) is based on the relative motion between the specimen and a magnetic field source. Due to the relative motion, eddy currents are induced in the specimen. In case of a defect, the induced eddy currents are perturbed as well as their secondary magnetic field. Measuring the secondary magnetic field enables defect detection and localization in the specimen under test.

Sun et al. (2) carried out an investigation on the basis of a permanent magnet, which is perpendicular orientated to the surface of the object under test and surrounded by a pick-up coil. The permanent magnet with the surrounding coil is moved relatively to the object’s surface. Evaluating the output voltage of the coil enables defect detection. Other approaches use a DC coil as stationary magnetic field source instead of a permanent magnet and giant magnetoresistance sensors (3) or pick-up coils (4) to measure the perturbation of the magnetic field.
Lorentz force eddy current testing (LET) is a MECT method based on force measurement to detect, localize and identify defects (5-10). Due to the relative motion between the permanent magnet and the object under test eddy currents are induced, leading to a Lorentz force acting on the conductor and the permanent magnet. In presence of a defect, the eddy currents and the Lorentz force are perturbed. Evaluating the force signal enables defect detection, localization, and identification.

Tan et al. presented a MECT method based on a diametrically magnetized cylinder magnet, rotating in the vicinity to an object’s surface (11). The study shows, that it is possible to distinguish between objects with and without defect by the variation of the magnets rotation speed as well as the electromagnetic torque acting on the magnet.

The investigation presented in (12) uses a rotating magnetic field, which is created by three-phase windings to induce eddy currents in the object under investigation. Due to the eddy currents the temperature of the investigated material increases. Temperature gradients at the object’s surface, which might result from defects, are evaluated by an infrared camera.

In this study, we present investigations on a portable version of the MECT method, where an arrangement of axially magnetized permanent magnets rotates in the vicinity to a fixed specimen. The secondary magnetic flux is measured by a pick-up coil to identify defects.

2. Measurement setup

The principle of the investigated portable MECT system is shown in Fig. 1 a). It consists of an arrangement of two axially magnetized cylinder magnets, which are fixed to a drive shaft. The drive shaft and hence the magnets are driven with the rotational velocity $n_0$ by an electric drive and induce eddy currents in the fixed specimen.

![Figure 1. a) Principle of the portable MECT setup. b) Experimental setup of the system.](image)

The drive is mounted at the system’s frame as well as the pick-up coil. A change in the magnetic flux penetrating the pick-up coil, results in an induced voltage in the pick-up coil. A data acquisition unit measures the voltage, which contains the information about the presence of a defect.
Figure 1 b) illustrates the experimental setup of the MECT system with the EC 45 flat 30 W motor from maxon motor (13), the magnet arrangement, the pick-up coil, the measurement frame, and the fixture for the specimen. The latter ensures an axisymmetric alignment of the MECT system and the cylindrical specimen. The mechanical design of the experimental setup enables the adjustment of the lift-off distances $h_{coil}$ and $h_{mag}$. Both are set to 1 mm. The relevant dimensions and information about the used magnets, the pick-up coil as well as the specimen are listed in Table 1. A PXIe-1078 chassis (14) with the embedded controller PXIe-8135 (14) and the data acquisition card PXIe-4497 (14) from National Instruments are appropriated for data acquisition. Furthermore, this system is used to control the motor speed using the motion controller EPOS2 from maxon motor (13).

<table>
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<tr>
<th>Table 1. Parameter of the permanent magnets, the pick-up coil, and the specimen used in the measurement setup.</th>
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<tr>
<td><strong>Permanent magnets</strong></td>
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<td>$D_{mag} = 7$ mm</td>
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<tr>
<td>$H_{mag} = 25$ mm</td>
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<tr>
<td>$D_h = 12$ mm</td>
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<td>Material: NdFeB N52</td>
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In this study, the induced voltage in the pick-up coil is evaluated for four different specimen scenarios. Besides measurements without specimen, three different types of specimen are investigated as shown in Fig. 2. Specimen 1 is a defect-free specimen. Specimen 2 and specimen 3 consist of a milled slit hole of 12 mm length, 4 mm width and 6 mm height (see Fig. 2d). The parameter $\alpha$ is the alignment angle between the specimen and the measurement frame.

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**Measurement results and discussion**

Pre-investigations showed that the alignment angle $\alpha$ influences the measured voltage in case of specimen with defect. Moreover, a certain rotation speed is necessary that a
difference between the voltage signal for the measurement in defect-free case and a measurement with defect can be recognized.

For each measurement the corresponding specimen is fixed at a specific angle $\alpha$ in the specimen fixture. Afterwards the rotation speed of the motor is set to the specified value. When the motor reached its target velocity, the induced voltage in the coil is measured with a sampling frequency of $f_s = 20$ kHz. Digital signal processing is done in a post process, analysing the measured signals in the time and frequency domain.

3.1 Proof of principle

To verify whether the introduced system is applicable to the defect detection in electrically conducting materials, a measurement without specimen, a measurement with specimen 1 (defect-free), and a measurement with specimen 2 is performed.

The results for the rotation speed $n_0 = 1800$ rpm and the alignment angle $\alpha = 0^\circ$ are presented in Fig. 3. The time signals $u$ are presented in multiple of the period time $T_0$ for one rotation of the magnet arrangement and the amplitude spectrum is shown for normalized frequency $f/f_0$, where $f_0 = n_0/60$ is the rotation frequency of the magnet arrangement.

Regarding the amplitude spectrum $|U|$ of the measured signals, it is observable that the second and the fourth harmonic are significant for the investigated setup and can give an indication of the presence of a defect. Further, the amplitude spectrum in case of no specimen and specimen 1 are similar in the relevant frequency range. In the time domain, the measured voltage in case of no specimen is noisier than the signals with specimen. Based on this fact, the presence of a specimen is detectable.

The amplitude of the second and especially of the fourth harmonic increase in case of a defect (specimen 2) compared to the measurements with specimen 1 and without specimen. Hence it can be stated, that the presented MECT principle can be used for defect detection in electrically conducting materials by evaluating the measured voltage.

It is possible to observe a change in the signals time and frequency domain, by comparing measurements without specimen or a specimen without defect and a specimen with defect.

It should be mentioned, that the induced voltage in the pick-up coil in case of no specimen and defect-free specimen differs in the signal-to-noise ratio and not in the amplitude spectrum for the relevant frequency range. Due to this fact, it is not necessary to use a reference specimen without defect for the calibration. The reference signal for a defect-free case can be gained by a measurement without specimen.

Assuming an ideal experimental setup (Fig. 1 a), a voltage in the pick-up coil should only be induced in case of a defect. Unlike this expectation, a periodic voltage is induced during the measurements, even in case without specimen. This fact leads to the conclusion, that there is a periodical change of the magnetic flux through the pick-up coil during the rotation of the magnets. It is caused by uncertainties in the magnetisation of the used magnets and manufacturing tolerances of the mechanical setup. A nutating behaviour can be observed as consequence of the mechanical unbalance of all rotating components in the experimental setup.
Figure 3. Induced voltage and corresponding amplitude spectrum for $n_0 = 1800$ rpm und $\alpha = 0^\circ$, in case of a) measurement without specimen, b) measurement with specimen 1 and c) measurement with specimen 2.

Additionally, uncertainty in the axisymmetric alignment of the rotating magnets and the pick-up coil contributes to the periodic change of the primary magnetic flux penetrating the pick-up coil during motion. 

As summary it can be stated, that uncertainties in the magnet’s magnetisation and the mechanical setup lead to a periodic change of the primary magnetic flux and hence to an induced voltage in the pick-up coil, even in defect-free case. In presence of a defect, the induced eddy currents are perturbed and the secondary magnetic flux changes periodically. The voltage induced by the time changing secondary magnetic flux is modulated on the induced voltage, which results from uncertainties in the mechanical system.
3.2 Influence of the alignment angle $\alpha$ on the measured signal

As pointed out before, the induced voltage in the coil depends on the alignment angle $\alpha$ between the specimen and the measurement frame. For that reason, measurements for specimen 1, 2 and 3 are performed with a rotation speed of $n_0 = 1800$ rpm, while the angle is varied from $\alpha = 0^\circ$ to $\alpha = 360^\circ$ in steps of $20^\circ$.

In order to evaluate the data, the amplitude spectrum of the measured voltage is calculated and the amplitude of the second harmonic $|U|_{H2}$ and fourth harmonic $|U|_{H4}$ are considered (see Fig. 4). For both, the amplitude in case of specimen 1 is independent to the angle $\alpha$. In contrast, the amplitudes in case of specimen 2 and 3 show a periodic change depending on $\alpha$. There are two periods of oscillations in the presented angle range for the second harmonic and four periods of oscillations for the fourth harmonic observable. Furthermore, the amplitude of the second harmonic decreases to the level of specimen 1 so that it depends on the angle $\alpha$, whether a defect can be detected or not by solely concerning the second harmonic. Looking at the fourth harmonic, results of the measurements with specimen 2 and 3 can be clearly separated from the measurements with specimen 1. Regarding the second and fourth harmonic and their dependency on $\alpha$, it can be observed that both have a maximum at $0^\circ$, $180^\circ$ and $360^\circ$. This fact indicates, that the location of the defect relative to the sensor system influences the system depending on $\alpha$ and hence the induced voltage in the pick-up coil.

![Figure 4. Measurement results for the influence of the alignment angle $\alpha$ on the measured signal for the second harmonic (a) and the fourth harmonic (b) in case of specimen 1, 2, and 3.](image)

In addition, there is a difference in the amplitude between specimen 2 and specimen 3 (see Fig. 4). Considering the different orientation of the defect in specimen 2 compared to the defect in specimen 3, the orientation of a defect with respect to the track of the rotating magnets results in a different amplitude of the induced voltage.

3.3 Influence of the rotation speed on the measured signal

In order to investigate the influence of the rotation speed on the induced voltage, measurements with different rotation velocities for specimen 1, 2 and 3 are performed. The amplitudes of the second and fourth harmonics of the induced voltage for an alignment angle $\alpha = 0^\circ$ and a velocity range from $n_0 = 100$ rpm to $n_0 = 2000$ rpm in steps of 100 rpm are shown in Fig. 5.
It can be observed that the amplitudes of the second and the fourth harmonics increase with an increasing rotation speed for each specimen. But in case of specimen 2 and 3 the amplitudes of the presented harmonics increase faster than in case of specimen 1. Furthermore, there is no continuous increase of the amplitude with increasing velocity of the magnets. Such unregularly values can also be detected in the presented result of the fourth harmonic. This irregularity might result from a changing oscillating behaviour of the rotating components depending on the rotation speed. Moreover, the study shows again, that the orientation of the defect with respect to the magnets track has an impact on the induced voltage.

4. Conclusions and outlook

A portable version of a MECT system to detect defects in electrically conducting materials is presented in this study. It consists of a rotating magnet arrangement which induces eddy currents in a fixed specimen. A pick-up coil, fixed to the sensor’s frame, is assembled relatively to the rotating magnet arrangement in an axisymmetric way and measures the magnetic flux.

The proof of principle shows, that the defect detection is possible in the time and frequency domain. Moreover, uncertainties in the magnetisation of the used magnets, the alignment of the pick-up coil relatively to the rotating magnet arrangement, manufacturing tolerances and the resulting mechanical unbalance cause a time changing, primary magnetic flux. In presence of a defect, the induced eddy currents and the secondary magnetic flux is perturbed. Both, the time changing primary and secondary magnetic flux, contribute to the induced voltage in the pick-up coil.

It has been shown, that the oscillating behaviour of the system influences the measured signal. It depends on the alignment angle $\alpha$ and the rotation speed $n_0$.

Future investigations will focus on different magnet arrangements for defect detection. Additionally, the influence of the defect position relatively to the sensor system will be studied as well as the correlation between the mechanical behaviour of the system and the measured signal.
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References