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Probe Optimization for Velocity Induced Eddy Current Testing in Aluminium

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Abstract- The railroad network requires constant inspection of rail integrity. Early defect detection is of utmost importance to maintain safety and reduce costs. This work proposes a new non-destructive probe configuration to be used in an inspection method based in eddy currents, which optimizes the detection of defects in a conductive material moving relative to the probe. This approach uses velocity induced eddy currents where the motion of a permanent magnetic field induces currents on the surface of the metal, and it is not restricted by the inspection speed limitations of more traditional methods. A differential sensing coil is used as a magnetic sensor that can detect current flow perturbations caused by the presence of defects.

I. Introduction

The monitoring and inspection of metal surfaces for defects in moving media is an area where ongoing research is fundamental. It is paramount for applications such as railroads, where currently the speed is a limiting factor that restricts the inspection to a dedicated bogie slower than trains moving in overcrowded commercial services. Rolling contact fatigue (RCF) cracks are one of the most common causes of train derailment [1] that needs to be prevented with non-destructive testing (NDT) methods. Some NDT methods capable of detecting these defects are flux-leakage [2-3], ultrasound [4], optical [5] and traditional eddy currents [6-7]. Due to the low inspection speed and to the need for a customized bogie, implementing these systems in commercial trains is still a problem that requires costly maintenance interruptions. This paper describes enhanced contributions to the implementation of a new inspection method based on eddy current testing (ECT), described in a rather general way in [8], which is a contactless method of inspection whose sensitivity increases with speed.

In traditional eddy current testing methods, an alternating magnetic field generated by an excitation coil is used to induce eddy currents in the metal. By measuring the excitation coil impedance or by using a magnetic sensor to measure the perturbations in the secondary magnetic field, generated by the eddy currents, it is possible to detect, locate and characterize cracks in aluminium [9]. Lorentz force eddy current testing (LET) detects metal discontinuities by measuring the opposing force being applied to the magnet throughout the motion caused by the induced currents [10]. When a defect disturbs the spatial current distribution, the Lorentz force will also be disturbed. The method described in this paper induces eddy currents in the same way as LET method, however instead of detecting force disturbances our method measures directly the eddy current's magnetic field perturbations [8]. An optimization of the probe geometry and magnetic sensor positioning that increases inducted eddy current density and defect detection is proposed in this paper.

The remainder of the paper is structured into four sections. In the following section a brief introduction to the NDT method using velocity induced eddy currents is made. In section III numerical modelling for different probe configurations using a finite element program to compute the stationary study, is described. Section IV contains the experimental validation that confirms the improvement of the method with the use of new probes by detecting four defects in an aluminium plate. Finally the conclusions and future work are summarized in section V.

II. Velocity Induced Eddy Currents Method

Traditional methods of eddy current testing use an alternating magnetic field to induce eddy currents in the material to be tested. If there are discontinuities in the electrical conductivity caused by a defect, the spatial distribution of the induced currents in the material is perturbed, which can be sensed by measuring the excitation coil's impedance or by using a magnetic field sensor to measure the resulting magnetic field perturbations. When the eddy current path is disturbed due to a crack or any other defect, the total magnetic field sensed by the magnetic sensor will also be disturbed.

Within this work permanent magnets moving at a constant speed over the metallic plate to be tested are used to induce the eddy currents in the material and a differential coil to sense the perturbation in the total magnetic field generated in the vicinity of the plate.

The rail defects known as Rolling Contact Fatigue (RCF) are defects that are essentially initiated on the surface or very close to the surface inside or on the head of the rails due to overstressing in the rail material. When using eddy current based methods to detect these defects, detection can be improved if the induced eddy currents have a direction perpendicular to the span of the crack, so that a greater perturbation occurs when the probe crosses it. This implies the direction of the eddy currents in the zone to be inspected to be the same as the motion of the probe, that is, along the railway.

In order to characterize the geometrical characteristics of a RCF crack, several scans have to be made by crossing the probe with the crack at slightly different intersection points, until all the crack length is looked over. To speed up the inspection process one can prevent these multiple scans, by imposing a flow pattern to the induced eddy currents containing a wide zone of currents with the same direction parallel to movement and with a similar intensity. At the same time, the measurement of the resultant magnetic field can be done simultaneously by an array of magnetic sensors placed in the vicinity of this zone of uniform current density as the area of metal being assessed in one scan is increased.

A study of the influence on the current density created by different configurations of the pair magnets and magnetic sensors included in the probe with numeric modelling and experimental validation is given below not only to understand the physical phenomenon involved but also to optimize the detection capabilities of the probe.

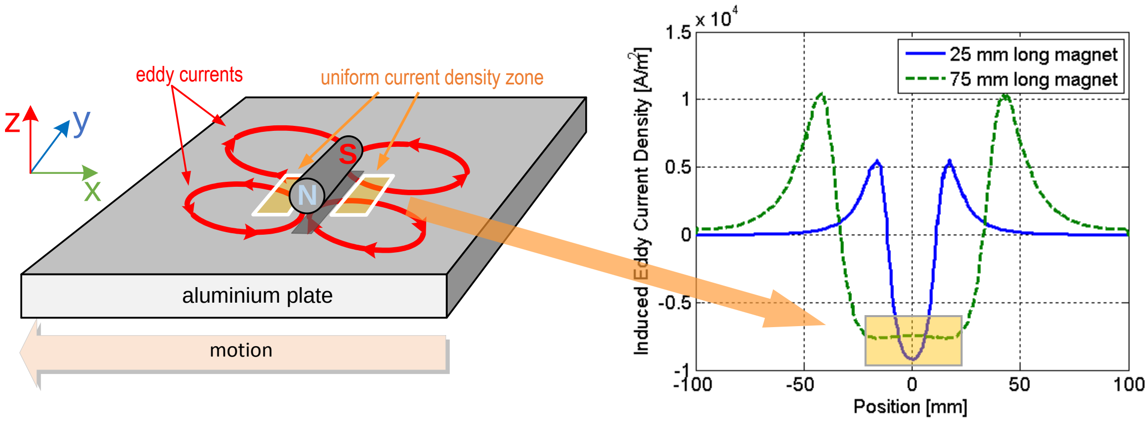
Two types of probe configurations have been considered: (1) one includes one single permanent magnet with its magnetization perpendicular to the motion axis and parallel to the surface under inspection in order to obtain in the surface two zones with an uniform current density on each side of the magnet as depicted in Fig. 1(a); (2) the other composed by multiple magnets having opposing magnetizations perpendicular to the surface to create multiple zones with the current direction perpendicular to the cracks as depicted in Fig. 2(a). Both probes include sensing coils strategically placed in order to determine the magnetic fields in areas where the current density has a more uniform distribution pattern parallel to the motion direction.

III. Numerical Modelling Based Studies

With the aim of gaining a better awareness of the effects that geometrical changes in the probe configuration have in the induced eddy current flow patterns and in the sensitivity to crack detection when the eddy currents are created by a DC magnetic field into relative motion with respect to the electrically conducting material to be inspected, a commercial finite element program (Cedrat COMSOL) was used. Simulations were carried out to predict the eddy current induced in an aluminium plate (100 mm x 100 mm x 4 mm) that moves at a velocity of 4 m/s in relation to a fixed probe holding different permanent magnet shapes and configurations simulated with the finite element model.

A. Single Magnet Probe

To provide an area in the metallic plate where the induced eddy currents have the direction of the displacement and uniform current density intensity, a possible implementation is presented in Fig. 1 (a), where *xx* axis indicates the direction of the probe and plate relative motion. The permanent magnet is placed with its magnetization perpendicular to the motion axis and parallel to the plate surface. In the vicinity of the magnet, there are two marked zones with the required eddy current pattern.



(a) (b)

Figure 1. (a). Eddy currents when a permanent magnet with magnetization along *yy* is in motion relative to a plate; (b) Eddy current densities measured in the uniform current density intensity zone marked in the pictures for a 25 mm and a 75 mm long permanent magnet.

Fig. 1 (b) depicts the induced current densities along an *yy* line that crosses the zone in front of the magnet with uniform current densities for a 25 mm and a 75 mm magnet lengths. The distance this line needs to be in relation to the magnet in order to obtain a uniform current density increases with the length of the magnet, hence for the 25 mm long magnet the distance is 8 mm and for the 75 mm long magnet it is 12 mm.

Cylindrical neodymium permanent magnets with 8 mm diameter, 25 mm of length and a 1 T remnant flux density magnetization along its length were chosen to be used in the model and experimentally due to their availability.
Despite the larger zone obtained with the 75 mm magnet, observing Fig. 1 (a) it is possible to observe that the increase of the distance between the zone and the magnet results in a lower uniform current density. This is due to the increasing distance needed between the zone and the permanent magnet needed to obtain the uniform current density. This can be avoided by using several magnets to create smaller multiple uniform current regions.
Another improvement that can be made to increase the eddy currents is related to the magnetization direction. By rotating the magnet to apply a vertical (along *zz*) magnetization, the magnetic flux that penetrates the metal is increased, thus increasing eddy current induction.
Taking all this into account, a new probe design was made using multiple magnets with vertical magnetization, which is described in the section below.

B. Multiple Magnet Probe

A simulation was carried out with multiple magnets with opposing vertical magnetizations to create multiple zones with the desired current orientation, uniformity and to increase the current densities in the measuring zones. The simulated eddy current densities and magnet placements are depicted in Fig. 2 (a). The same cylindrical magnets were used as in the first probe.

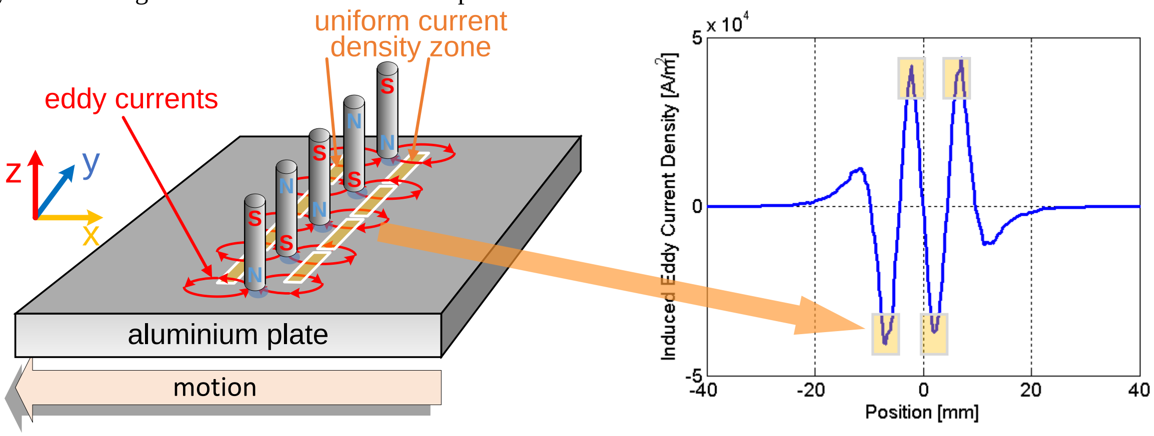


Figure 2. (a) Eddy currents when moving vertical permanent magnets along *xx* with opposing magnetizations.
(b) Eddy current density measured 3 mm away from the permanent magnets.

Fig. 2 (b) depicts the current densities measured in a line crossing the uniform current zones 3 mm in front of the magnets. Peaks with similar intensity can be observed in the marked zones. The value of these peaks is significantly larger than those obtained with the single magnet probe and the area above their location is used to measure the magnetic field perturbations. Larger current perturbations will occur when crossing over a crack, thus the probe sensitivity to cracks is increased.

IV. Experimental Validation

A. Experimental Setup

To verify the results obtained with the simulation, the experimental setup depicted in Fig. 4 was assembled. It contains a linear belt drive actuator, with a motor controller/driver from Parker capable of achieving speeds up to 6 m/s that moves the probe with a position accuracy of 0.083 mm. The output voltage from the magnetic sensor is acquired by a 16 bit 1.25 MS/s DAQ (USB-6251 from National Instruments) and a personal computer running Matlab software completes the measuring system.

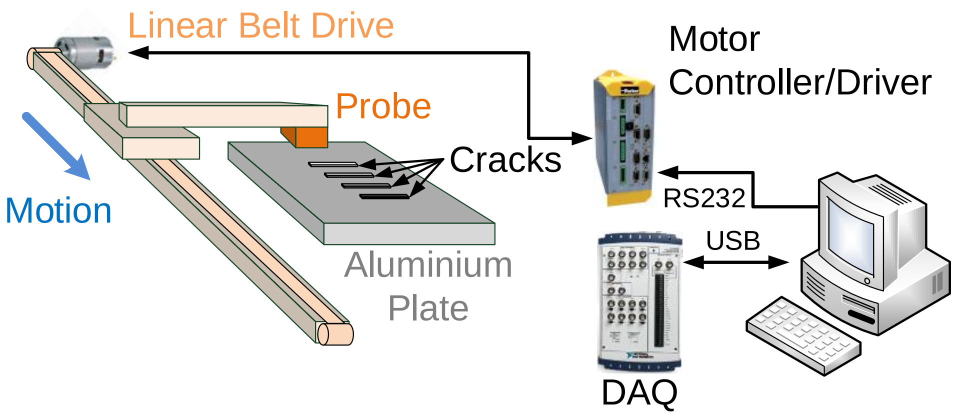


Figure 4. Experimental setup.

The sample tested was an aluminium sheet 4 mm thick with four machined linear defects on its surface. All defects have 0.5 mm of width, 50 mm of length and their depths are respectively 2.5, 3.0, 3.5 and 4 mm.
The magnetic sensor used in both probes is a differential sensing coil composed by two 4.7µH radial inductors with ferrite core from Murata Power Solutions. In the single magnet probe, the two differential coils are placed above the zones with uniform eddy currents in front and behind the magnet. In the multiple magnet probe their positions are above both current peaks that appear 3 mm away from the gaps between each pair of magnets. In both cases the coils orientation is such that they are most sensitive to variation of currents in the *xx* axis, thus they are placed very close to the plate with their core parallel to *yy*. The voltage output from the differential coils is amplified 100 times using an INA118 instrumentation amplifier.
To sample the plate, first the probe is accelerated to 4 m/s. While it is kept at that constant speed it crosses the defects approximately in their middle and the DAQ acquires one sample each 0.083 mm of probe movement. Finally it is decelerated to a full stop. The lift-off distance between the plate and probe is approximately 1 mm.

B. Experimental Results

The experimental data was obtained by moving the probe across the defects at a constant speed of 4 m/s. Fig. 5 depicts the sensing coil output voltage measured when a scan above the midline of the evenly spaced 2.5, 3.0, 3.5 and 4.0 mm deep defects with single and multiple magnet probes is performed. In the case of the multiple magnet probe the data depicted is the output voltage of the couple of coils at the probe centre.

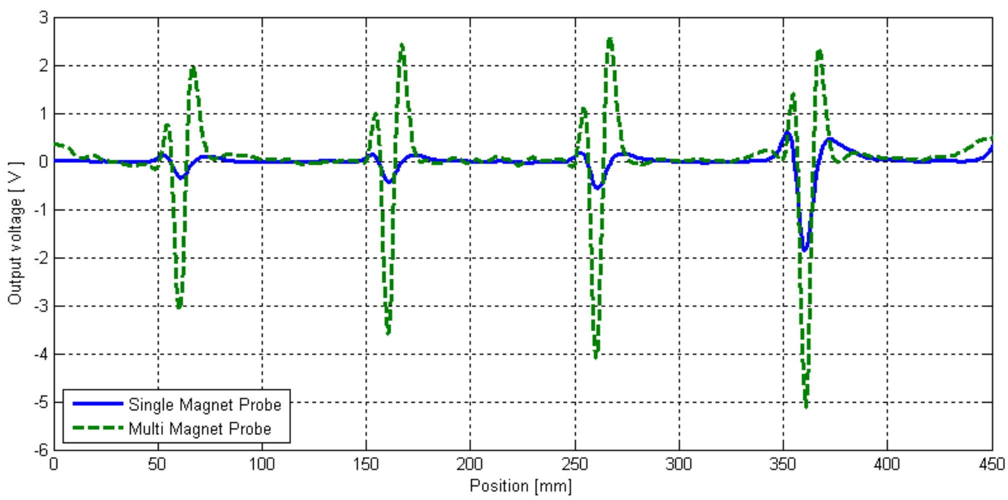


Figure 5. Experimental output voltage for single and multiple magnet probes scanning the four cracks at 4 m/s.

By observing both experimental curves it is possible to notice an increase in the signal amplitude as the probes cross deeper cracks. This makes it possible to further analyse the crack in terms of depth. The probe with multiple magnets has higher magnetic field perturbations which are the result of higher current densities induced in the sampled metal.

V. Conclusions

To improve detection capabilities of linear defects when eddy currents based methods are used the induced eddy currents must have a direction perpendicular to the defect length and if an uniform current density is reached then the inspection process can be speed up with the use of an array of magnetic sensors. This paper tests several probe configurations to enhance their detection capabilities with finite element model simulations and experimentally.

Simulation results proved that to obtain uniform current density in an area large enough to test RCF defects, a single magnet probe with variable length was required. As this is not a practical solution, a configuration of a probe with multiple magnets was modelled and simulation proved that multiple zones with the same current density were attained. The experimental results validated the model and successful scans were made with both solutions.

As future work it would be relevant to try to increase the magnetic flux density that penetrates the metal by assembling the magnets in a Halback array and to apply the measurement system to detect defects in a ferromagnetic material.

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