Electromagnetic Non-Destructive Evaluation (XXI)
D. Lesselier and C. Reboud (Eds.)

doi:10.3233/978-1-61499-836-5-17

A New Probe for Velocity Induced Eddy Current Inspection

Helena Geirinhas RAMOS[a,1] , Tiago ROCHA[a] and Artur Lopes RIBEIRO[a]
[a]*Instituto de Telecomunicações, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*

Abstract. Velocity induced eddy current inspection is a technique to inspect conductive materials. It has a good detection performance and is particularly well suited to situations where the speed is a factor to be considered because its sensibility increases with the moving speed. This paper assesses the field produced by several probe geometries in the detection of linear machined defects. A more detailed analysis is carried out for a probe that includes an array of cubic magnets to induce the eddy currents inside the sample and Hall sensors to measure the resultant magnetic field.

Keywords. Nondestructive testing, eddy current testing, velocity-induced eddy current testing, Hall sensor.

1. Introduction

Preventive maintenance is a critical issue in safety and cost of several industrial applications [1, 2]. Due to its high sensitivity eddy current testing is one of the most used techniques to inspect conductive materials [3, 4]. A modified version of this method was proposed [5, 6] to fit out situations where there is a relative motion between the material to be inspected and the equipment that performs the measurement. The basic physical phenomena of this method, designated velocity induced eddy current is based on the interaction of a stationary magnetic field and a specimen which moves with a constant speed in relation to that field. It is a very sensitive method and reduced power is needed to apply the technique as no excitation current is required.

The literature [7-9] mentions that the performance of the method depends greatly on the configuration of the magnets included in the probe and also in the assessment of the magnetic field. Enhancements can be achieved not only by increasing the magnetic flux density in the material to be inspected, but also, by choosing the best position for the magnetic sensors. This paper reports results obtained experimentally for several probe geometries. It studies data measured with different probes when a sample with machined cracks is inspected. The study is presented step by step, meaning that, incremental

[1] Helena Geirinhas Ramos, Instituto de Telecomunicações, Instituto Superior Técnico, Av. Rovisco Pais, 1, 1049-001 Lisboa, Portugal; E-mail: hgramos@ist.utl.pt

enhancements are added to the probe and results are observed and compared. A compromise between weight and volume was also considered. It was concluded that a probe consisting of an array of cubic magnets that have alternating vertical magnetization and a set of small Hall effect sensors placed in the interstices showed the best performance to evaluate machined cracks in a plate using velocity induced eddy current inspection technique.

The remainder of the paper is structured into four sections. In the following section the experimental setup is shown. In Section 3 after a brief introduction to the NDT method using velocity induced eddy currents, enhancements to previous designs of the magnet source and of the detection sensors are proposed. Section 4 contains the experimental validation that confirms the improvement of the method with the use of a new probe by detecting four defects in an aluminium plate. Finally the conclusions are summarized in Section 5.

2. Experimental Setup

Using the experimental setup shown in Fig. 1. a sample of 4 mm thick 1050 aluminium plate with four machined defects was inspected. All defects are 50 mm long, 0.5 mm wide and depth varies from 0.5 mm to 2 mm with intervals of 0.5 mm. It was scanned at a fixed speed of 4 m/s.

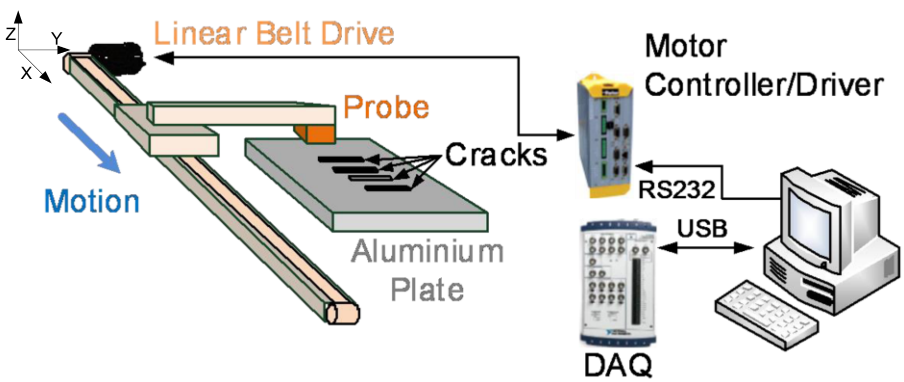

Fig. 1. Block diagram of the experimental setup.

The probe includes magnets to produce eddy currents and magnetic sensors to measure the magnetic field in the vicinity of the sample. Details about the experimental setup are described in [5].

3. Velocity Induced Eddy Current Method

In the velocity induced eddy current inspection method used in this work, it is a constant magnetic field produced by a permanent magnet that generates induced eddy currents, when the magnet moves at a constant speed over a metallic plate. This permanent magnet source is included in the probe represented in the setup depicted in Fig. 1.

The perturbations in the total magnetic field generated in the vicinity of the sample are assessed using Hall sensors also included in the probe.

3.1. Magnetic Field Source

The magnetic field generated by a coil with a constant current is hardly matched by the one that is generated by neodymium magnets (NdFeB). The remanence field property of a NdFeB magnet can be greater than 1 T, which makes them the strongest type of permanent magnets commercially available to date. For this reason this type of magnet was chosen to be implemented in the velocity probes developed within this work.

The shape and orientation of the permanent magnet is a key factor to induce the desired current distribution. The initial probe designed to perform velocity ECT inspection was based in previous experience that the sensitivity to defects is increased if all currents are perpendicular to the defect, because it is the case where most current perturbation occurs.

In [8] different moving magnetic probes were used to detect surface defects in electrically conductive metal. Two types of probe configurations were considered: (1) 'Sleeping magnet probe' which includes a single permanent magnet with its magnetization perpendicular to the motion axis and parallel to the surface under inspection; (2) 'Standing magnet probe' composed by two magnets having opposing magnetizations perpendicular to the surface under inspection. It was concluded [4] that the configuration (2) creates two smaller zones of uniform current density with the current direction perpendicular to the cracks when the probe moves along the sample. The value of eddy surface current density amplitude in these zones of uniform current is larger than the maximum current density amplitude obtained with the "sleeping magnet" simulation.

Since higher current density results in higher perturbations during the interaction with a crack, then the probe sensitivity to cracks is increased in 'standing magnet probes', due to the higher current densities that are induced by the two magnets. This configuration was generalized to multiple "standing magnets", meaning that multiple magnets are placed next to each other with alternating magnetization. By placing each loop next to another loop with reversed current direction, a focused zone with the current along x can be obtained. Also it improves the current density by positioning the magnet vertically (z magnetization). The magnetic flux that penetrates into the metal is increased, thus increasing eddy current density.

After that, a probe with a matrix of permanent magnets, as the one schematically represented in Fig. 2.(a), that have alternating vertical magnetizations was developed and built. By placing the additional row of magnets, with opposing magnetization direction, next to the previous one, the derivative of the magnetic flux will increase as the probe moves above the metallic plate. A numerical simulation was made using Comsol software for the configuration represented in Fig.2 (a) containing two rows of alternating magnets. To constrain the span of the induced current loops (thus increasing the density of current eddies), cubic neodymium magnets with 5 mm of edge were used in both simulations and experimentally. These magnets were chosen not only because they are widely availability but also because the interstitial space between magnets can be used to position the Hall sensor. In this case, a 6 mm resolution is achievable (the spatial span along y axis of each loop is restrained to the length of the cube plus the 1 mm spacing of the Hall sensor, which equals to 6 mm). The top view of the probe's finite element model moving at 4 m/s, with the outline of the six magnets and eddy current pattern are depicted in Fig. 2 (b).

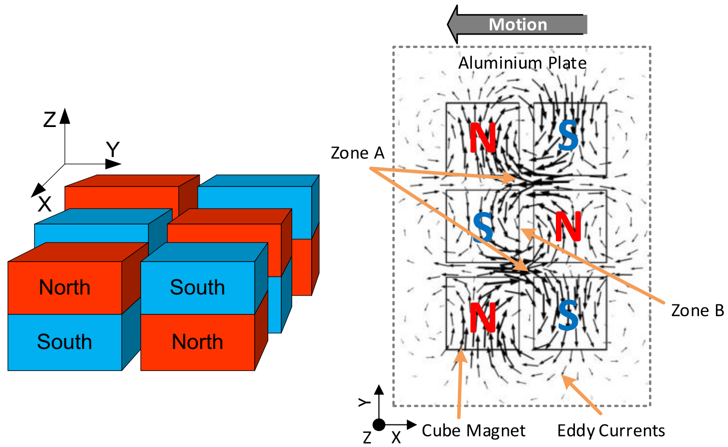

Fig. 2. (a) Magnet Probe assembly; (b) Eddy current distribution induced in the moving Al plate surface.

The maximum value of current density located in the surface in the single magnet model the maximum value obtained of eddy current density was 2.0×10^7 A/m^2, and it is located behind the magnet. In the improved probe this value was increased to 3.4×10^7 A/m^2 and the location is in the two zones A depicted in Fig. 2 (b).

3.2. Magnetic Sensor

[9] reports and analyses in detail data measured with three different magnetic sensors when a sample with machined cracks perpendicular to the eddy currents induced in the material are inspected using velocity induced eddy current method. The sensors used are a differential pick-up coil, a commercial magnetic sensor based on giant magneto-resistors (GMR) and a Hall sensor.

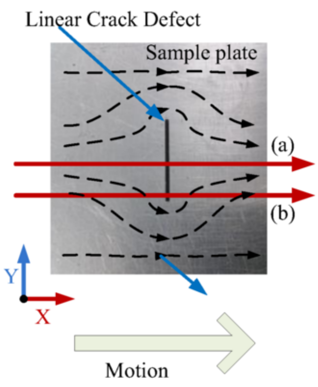

Fig. 3. Permanent magnet positioning and current flow perturbation due to the presence of a defect; paths covered by the magnetic sensors.

Due to the different nature, position and orientation of each of the magnetic sensors, a different optimal crossing point between the sensor scan path and the linear defect are obtained for each sensor, in order to maximize its detection sensitivity.

Fig. 3 shows a pictorial representation of the eddy current perturbations in the metallic sample when a linear crack is inspected if all the induced currents were considered parallel and in the direction of the motion. This is a very raw simplification, as these currents only temporarily appear in front and behind the permanent magnet as it moves above the plate. Nevertheless, it allows drawing conclusions about the best scanning path of each sensor in order to increase defect sensitivity.

The two paths along the movement direction, (a) and (b), will be travelled by the probe to obtain the magnetic field values that may inform about the existence of the crack. Thus, one may expect that when crossing the defect along the path (a) (in the middle of the crack), if the magnetic sensor sensing axis is in the y-direction, then the magnetic field has a minimum due to the conductivity discontinuity caused by the crack. For the same reason, if the magnetic component to be detected is along x then the path to be traversed must be (b) and two peaks (one negative and another positive) are observed. Taking these observations into account and because each magnetic sensor measures a different component of the magnetic field density, in [5] it was concluded that Hall effect sensor is more advantageous than either the GMR sensor or the differential coil. In fact, the GMR sensor can only detect the defect if the measurement is taken along the path crossing the edge of the defect and its polarization is rather difficult due to the magnet vicinity. In the cases of the pick-up coil and Hall sensor, the best crossing point between the scanning path and the defect should be in the center of the defect (path (a)). As these sensors are sensitive to x oriented currents, the maximum perturbations in the x oriented eddy currents occur in the intersection point between path (a) and the defect. The waveform for the Hall sensor contains one peak and the pick-up coil probe contains a derivative of the Hall sensor signal. The Hall sensor measures magnetic flux density and differential coils its derivative, therefore, more difficult to interpret.

3.3. Probe Design

The probe used to inspect the 4 mm thick 1050 aluminium plate with four machined defects using velocity induced eddy currents includes an array of 3x2 cubic neodymium magnets with 5 mm of edge to create the source magnetic field and Hall effect sensors to measure the resultant magnetic density field. All defects are 50 mm long, 0.5 mm wide and depth varies from 0.5 mm to 2 mm with intervals of 0.5 mm.

The placement of each Hall effect magnetic sensor is of great importance, as it must be able to sense the magnetic field perturbations caused when crossing a defect. From Fig. 2. one concludes which is best component of the magnetic field to sense current perturbations can be predicted. B_x is not a good choice, as the only possible location for the sensor is between the two magnets in zone B, where the contribution to B_x is self-nulling due to the curling nature of the induced currents. Also from Figs. 2 and 3, one can expect that measuring B_y in zone A and B_z in zone B will provide good results. In zone A the currents are oriented along x axis, which results in a B_y perturbation when they are interrupted. To be noted that the perturbations measured in zone B are mainly caused by interruptions to the loop of currents centered in zone B, however the perturbations in a zone A will be a contribution from both loops of current that crosses this zone.

4. Experimental Results

To validate the simulated results, an experimental setup was assembled with two probes, where each one differs on the placement of the magnetic sensor in zones A and B measuring B_y and B_z respectively. Two probes were created with the array of magnets with opposing magnetizations to maximize the induction of eddy currents, and they differ on the location of the magnetic sensor. The Hall sensor was placed in zones A and B as depicted in Fig. 2. The probe with the sensor in zone A is named Probe A and similarly Probe B is the one with the sensor above zone B. Fig. 4 depicts the profile of the two

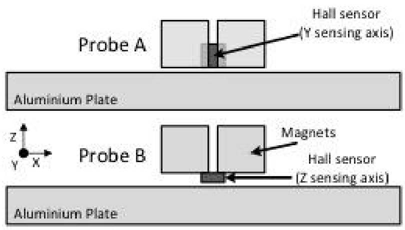

Fig. 4. Experimental results: (a) Representation of the two assembled probes.

To validate the simulated results, two probes were built with the array magnets with opposing magnetizations and with the Hall sensor placed in zones A (Probe A) and B (Probe B) as depicted in Fig. 4. Using the experimental setup shown in Fig. 1 the sample of aluminium was scanned.

To obtain the best possible experimental results, the lift-off should be minimized. Despite the 1 mm lift-off used in the simulation model, the lift-offs used experimentally differ for each probe as observed in Fig. 4. Probe A has the Hall sensor placed in the interstitial space between four magnets, so the magnets and Hall sensor have approximately 0.2 mm of lift-off. However, Probe B has the sensor laid flat between the plate and the magnets, which increases the distance between magnets and the surface of the aluminium plate to about 1.2 mm (1 mm due to the thickness of the Hall sensor and approximately 0.2 mm between sensor and aluminium).

The first experimental result was obtained by scanning the defects in the aluminium plate with both probes A and B. The probes scanning paths crossed the middle of the 50 mm long defects with 0.5, 1.0, 1.5 and 2.0 mm of depth at a fixed speed of 4 m/s. Figure 5 depicts the Hall sensor voltages acquired when scanning the aluminium plate.

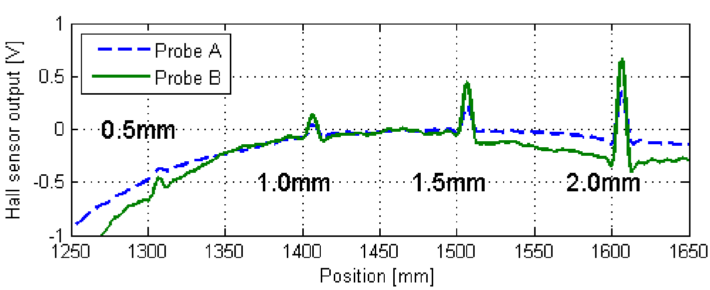

Fig. 5. Experimental results: (c) Differential output voltage from probe A and Probe B.

The characteristic waveform of a defect is composed by a positive peak preceded and followed by two smaller negative peaks. The positive peak is caused by the defect interrupting the loop centered on the zone B in Fig. 2. The other two smaller peaks appear when the defect interrupts each loop in front and behind zone B. When this occurs, some current will switch from flowing in the perturbed loop to flow in to the zone B loop. Some noise due to slight variations in the lift-off distance can also be observed in Fig. 5. To remove this noise, the output voltage from the Hall sensor was differentiated in MATLAB and the obtained result is depicted in Fig. 6.

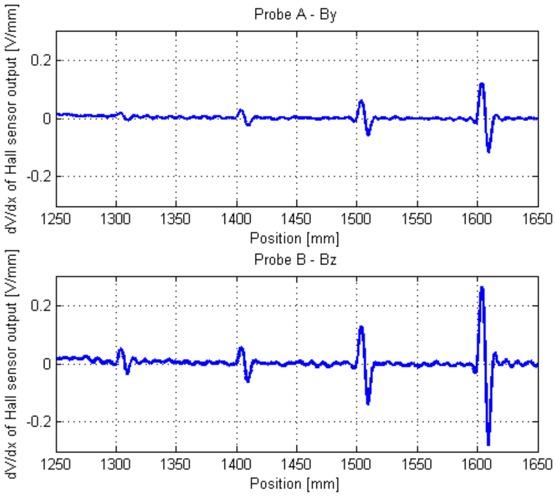

Fig. 6. Experimental results: (c) Differential output voltage from probe A and Probe B.

Observing the obtained signals in Fig. 6, it is possible to identify the four defects with both probes.

Despite having a larger lift-off than probe A, probe B shows approximately twice the signal amplitude in all defects, so it can be concluded that Probe B has greater sensitivity to defects.

5. Conclusions

The results obtained with the probe with two rows of permanent magnets showed that it is possible to constraint the loops of induced currents and thus increase their density, and in turn, the sensitivity to defects. The optimal location of the magnetic sensor was verified experimentally. This probe design was based on all the insights gained with the previous probe designs. It showed the best results and highest sensitivity out of all the probes previously studied and was able to detect a 0.5 mm deep superficial defect, which is a complex task to do even with conventional ECT.

The chosen design is capable of being scaled and also arrayed, which makes it versatile. Also, it is possible to detect defects with any orientation by using two probes, one in front of the other, and shifted by half the size of the cubic permanent magnet edge. The study made for aluminium specimens was successfully made, and the developed probe can be used to perform inspections in conductive non-ferromagnetic materials.

Acknowledgement

This work was developed under the Instituto de Telecomunicações project Relim and supported in part by the Portuguese Science and Technology Foundation (FCT) project: UID/EEA/50008/2013. This support is gratefully acknowledged.

References

[1] Libby H. L, Introduction *to Electromagnetic Nondestructive Test Methods*, John Wiley &Sons, Inc., New York, 1971.

[2] Zhijun Chen, Jianqing Xuan, Ping Wang, Haitao Wang, Gui Yun Tian, Simulation on high speed rail magnetic flux leakage inspection, in 5th IET Conference on Railway Condition Monitoring and Non-Destructive Testing, pp. 1–6, Derby, 29 November 2011.

[3] B. Venkatrama, B. Rao, *Practical Eddy Current Testing*, Alpha Science, B.P.C. Rao, 2007.

[4] S. Udpa, L. Udpa, Eddy current testing are we at the limits, Proceedings of 16th WCNDT 2004, August, 776 (2004).

[5] M. Zec, R. P. Uhlig, M. Ziolkowski, and H. Brauer. Finite element analysis of nondestructive testing eddy current problems with moving parts. IEEE Transactions on *Magnetics*, **44** (8) (2013), 4785–4794.

[6] H. G. Ramos, T. Rocha, D. Pasadas, A. L. Ribeiro, "Faraday Induction Effect Applied to the Detection of Defects in a Moving Plate", *39th Annual Review of Progress in Quantitative Nondestructive Evaluation*, *AIP Conf. Proc.*, **1511** (2012),1490-1497.

[7] Robert P. Uhling, Mladen Zec, Hartmut Brauer, André Tess, "Lorentz Force Eddy Currents Testing: a Prototype Model", *J. Nondestruct. Eval.* **31** (2012), 357-372.

[8] H.G. Ramos, T. Rocha, A.L. Ribeiro, D. Pasadas, "GMR versus differential coils in velocity induced eddy current testing", *Instrumentation and Measurement Technology Conference (I2MTC) Proceedings*, pp. 915–918,12–15 May 2014.

[9] Tiago J. Rocha, Helena G. Ramos, A. Lopes Ribeiro, Dário J. Pasadas, Chandra S. Angani, "Studies to Optimize the Probe Response for Velocity Induced Eddy Current Testing in Aluminium", *Measurement* **67** (2015), 108–115.

[10] Tiago J.Rocha, Helena Geirinhas Ramos, A. Lopes Ribeiro, Dário J. Pasadas, "Magnetic Sensors Assessment in Velocity Induced Eddy Current Testing", *Sensors and Actuators A: Physical*, **228** (2015), 55-61.