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

doi:10.3233/978-1-61499-836-5-160

Depth Crack Evaluation Using Multi-Harmonic Excitation and GMR Sensors

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Abstract. This paper reports an experimental study to detect and distinguish surface and sub-surface cracks in non-ferromagnetic materials using eddy current testing with a multi-harmonic excitation signal. A minimization of the crest factor of the excitation signal was done using a Shapiro-Rudin phase sequence. The chosen range of frequencies was based on a corresponding range of standard depths of penetration (SDP) in order to ensure that the eddy currents penetrate more or less an aluminum plate with 4 mm of total thickness. Experimental tests were realized on surface and sub-surface cracks with depths of 0.5, 1, 1.5 and 2 mm. The results obtained by the ECT probe are analyzed in the frequency domain.

Keywords. Eddy current, multi-harmonic signal, Shapiro-Rudin sequence, crack inspection.

1. Introduction

Nowadays non-destructive testing and evaluation (NDT&E) plays an important role to monitor the material condition of industry components. To date, several methods of NDT&E have been developed [1].

In the case of metallic structures, eddy current testing (ECT) is a well-known method used to detect, locate and geometrically characterize the cracks [2-3]. In the last decades, the research activity has been focused on the development of new eddy current testing approaches capable to provide more information about the crack presence in metallic structures [4-5].

Due to the nature of the eddy current phenomena, the eddy current density in a conductor is maximum at the material surface and it is attenuated with increasing depth. For a given material, the standard penetration depth (δ) of the eddy currents changes as a function of the testing frequency (f). A single sinusoidal current excitation with a fixed frequency can be imposed to a coil to induce eddy currents in the metallic surface [6]. The use of a more complex excitation current signal (such as a multi-frequency signal) allows the penetration of eddy currents in the material at different levels providing a richer spectral content [7].

For this purpose, this paper presents an experimental study performed to distinguish surface and sub-surface cracks using a multi-harmonic excitation signal with equal harmonic amplitudes and phases in a Shapiro-Rudin sequence. The obtained results are analyzed in the frequency domain.

2. Measurement System

The measurement system includes an ECT-based probe with a planar coil and a GMR sensor, a x-y positioning system, a function generator, a power amplifier and a multifunction data acquisition (DAQ) board, as depicted in figure 1. The planar coil was carefully positioned to induce eddy currents perpendicular to the crack line, and generates a magnetic excitation field parallel to the crack. The GMR sensing axis was fixed parallel to the crack measuring the component of the magnetic field on that direction (B_x). This field component contains the strong excitation magnetic field and the field perturbation originated by the presence of the crack. A special care must be taken in order to avoid the field sensor saturation. This component was chosen because it is much smoother than the other two components, with a maximum value over the crack central point. An instrumentation amplifier with G=27 dB was used to amplify the GMR output voltage to a suitable range of the DAQ board. The instrumentation amplifier and the GMR sensor were powered by a power supply of ±12V. A PXI-1036 Chassis from National Instruments was used to control the positioning system by RS232 interface and the AFG3012 function generator from Tektronix by GPIB interface. The TS200 power amplifier was used to amplify the multi-harmonic signal produced by the function generator to impose an excitation RMS current of 800 mA in the coil. The NI-PXI-6251 DAQ board inserted in the PXI Chassis was used to monitor the excitation current through a sampling resistor (R) connected in series with the coil and to measure the magnetic field from the GMR sensor. A Matlab program running in a desktop personal computer controls the complete system. The multi-frequency signal was created in the Matlab program and stored in the function generator when the scan begins.

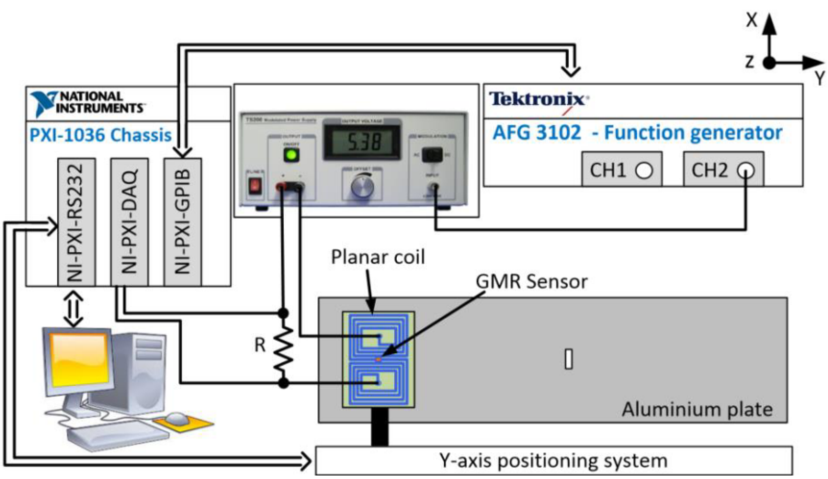

Figure 1. Measurement System.

2.1. Multi-tone signal

A multi-tone voltage signal was imposed to the coil to obtain a wide group of frequencies that allows the eddy currents to penetrate the material into different layers. Sinusoidal tones were combined in the following form:

$$s(t) = \sum_{k=1}^{N} A_k \cos(2\pi k f t + \alpha_k) \quad \textbf{(1)}$$

where k represents the number of the harmonic tone, A_k is the imposed current amplitude of each sinusoid, f is the fundamental frequency, α_k is the phase of each sinusoid, and N is the number of tones. All tones were generated with equal current amplitudes ($A_{kef} = A_{ef}$) which means that the root mean square value of the current signal $s(t)$ is given by:

$$S_{ef} = \sqrt{\sum_{k=1}^{N} A_{kef}^2} = \sqrt{N \times A_{ef}^2} = A_{ef}\sqrt{N} \quad \textbf{(2)}$$

Considering a phase value equal to zero (α_k =0) in each sinusoid of the multi-frequency signal, a strong amplitude peak value will be concentrated at the instants t = kT_0, T_0 being the period of the fundamental frequency. If this amplitude peak value is too high, problems related to the saturation of the GMR sensor, to the instrumentation amplifier and even to the signal generator will arise. Figure 2(a) shows the distribution of the amplitudes of a multi-harmonic signal (with 128 tones) computed with zero phases (for each sinusoid). In order to reduce the amplitude peak of the generated multi-tone signal, the α_k value of each sinusoid was carefully chosen. The Shapiro-Rudin sequence was used to determine the α_k values that allow the minimization of the crest factor of the excitation signal [8]. To form the Shapiro-Rudin sequence, the number of tones was considered as a power of 2, and the the α_k value of each sinusoid equal to zero or equal to π. Figure 2(b) shows the distribution of the amplitudes of a multi-harmonic signal (with 128 tones) computed with the Schapiro-Rudin sequence.

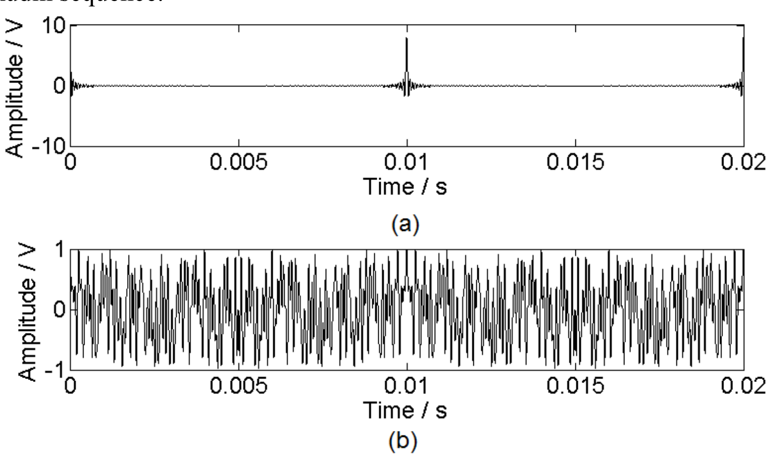

Figure 2. Representation of the amplitudes distribution of a multi-harmonic signal with 128 tones: (a) with zero phase for each tone; (b) with optimized phase choice for each tone using the Schapiro-Rudin sequence.

3. Experimental Scanning Test

The experimental tests were performed in an aluminum 1050 alloy plate widely used in the metallic industry. A multi-harmonic signal with 128 tones (between 100Hz and 12.8 kHz) was imposed to the coil to allow the eddy currents to penetrate the aluminum plate with 4 mm of thickness in different layers. For the aluminum under test, this range of frequency ensures that the eddy current penetrates at deeper levels with a standard depth of penetration equal to 0.7 mm for f=12.8 kHz and equal to 8 mm for f=100 Hz. The first experimental tests were done to evaluate a surface crack and a sub-surface crack with 8 mm of length and 2 mm of depth. This means that the first tests were performed for cracks with 50% of the thickness of the sample plate under test. Figure 3 depicts the scan tests that were performed. The y-axis positioning system moved the ECT probe with steps of 1 mm in a straight line of 30 mm above the center region of each crack.

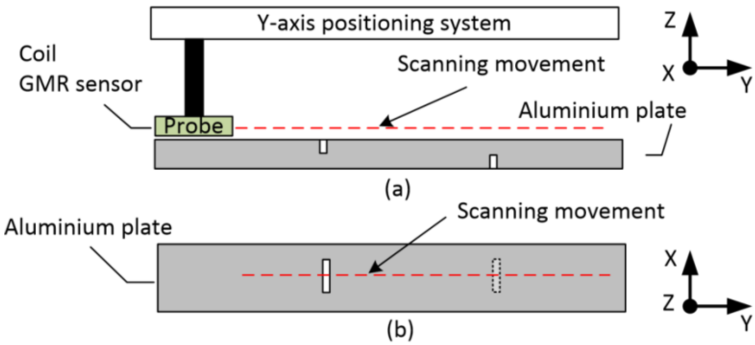

Figure 3. Representation of the performed scan: (a) Side view; (b) Top view.

The magnitude of the multi-frequency current signal was monitored by spectral analysis of the voltage at the sampling resistor *R* connected in series with the planar coil. A constant spectral current amplitude of 70.7 mA was imposed to the coil, resulting in a total amplitude current of 800 mA. Figure 4 depicts the magnitude of the measured magnetic field component B_x obtained by the GMR sensor for the case with the probe closer to the aluminum plate in a region without crack.

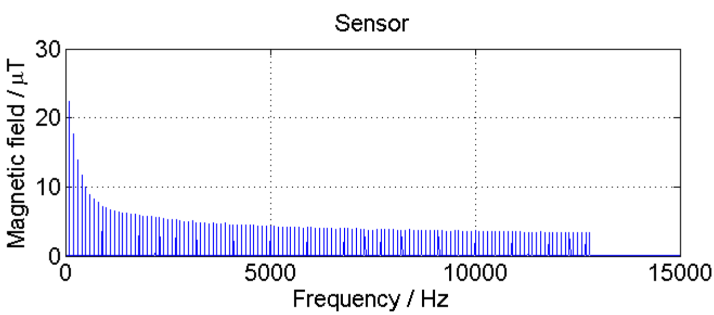

Figure 4. Magnitude Spectrum of the GMR Sensor response when the probe is closer to the aluminum plate in a region without crack.

From figure 4, it is possible to say that the magnetic field response decreases when the frequency increases. As expected, this is due to the induction of a higher eddy current density region at the surface of the plate when the testing frequency increases, which causes a decrease in the resulting B_x component.

Figure 5, depicts the magnitude of the perturbed magnetic field component B_x obtained in a series of points above the two cracks region and along a straight line crossing the crack perpendicularly. Figure 5(a) depicts the spectral content obtained for the surface crack with 8 mm of length and 2 mm of depth, while figure 5(b) depicts the spectral content obtained for the sub-surface crack with the same dimensions, but located on the other plate side. Note that the graphs were plotted after removing the baseline obtained in figure 4 in order to only obtain the perturbed magnetic field originated by the presence of the cracks.

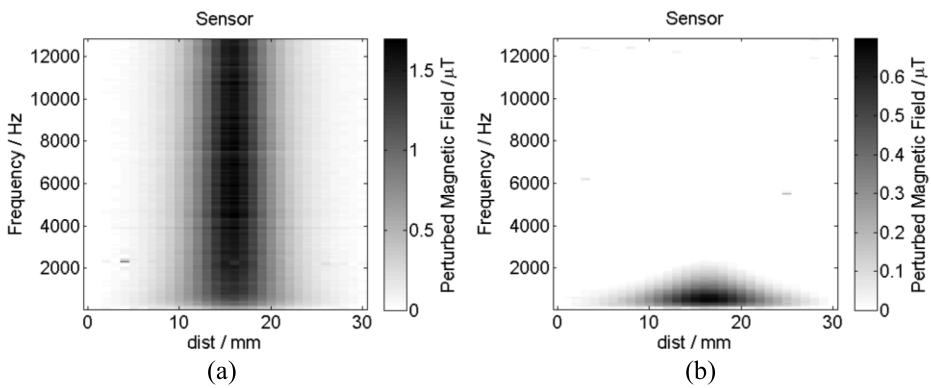

Figure 5. Perturbed magnetic field obtained from the GMR Sensor in a straight line of 30 mm above the center region of each crack: (a) Surface crack; (b) Sub-surface crack.

From figure 5, it is possible to observe that both perturbed magnetic field maps contain information about the dimensions of the cracks and both perturbed fields allow the classification of the cracks as superficial or sub-superficial. From figure 5(a), it can be seen that the value of the perturbed magnitude of B_x is approximately constant in the crack region for the group of 128 tones. This means that the perturbed magnetic field occurs for all the frequencies. From figure 5(b), it is possible to observe that the value of the perturbed magnitude of B_x is dominant in the lower frequency of the spectrum. The peak values of the perturbed magnetic field maps provide the y-axis position of the two cracks. In the y-position of the crack, the spectral magnitude of the perturbed magnetic field contains important information about the dimensions of the cracks. The high number of tones (128) was chosen to obtain a large magnitude spectrum with the information retrieved from the perturbed eddy currents at different layers. However, from figure 5, it is possible to observe that a range of lower number of tones could be used to distinguish the tested surface and sub-surface cracks. This means that the total current value of the excitation signals could be reduced using a lower number of tones. For this purpose, a new multi-harmonic signal with 32 tones was built and experimentally tested for the inspection of surface and sub-surface cracks with depths (d) of 0.5, 1, 1.5 and 2 mm. The experiments were performed in the same aluminum plate with a thickness of 4 mm.

Figure 6(a) shows the spectral magnitude of the perturbed magnetic field in the y-position of each surface crack. Figure 6(b) shows the spectral magnitude of the perturbed magnetic field in the y-position of each sub-surface crack. .

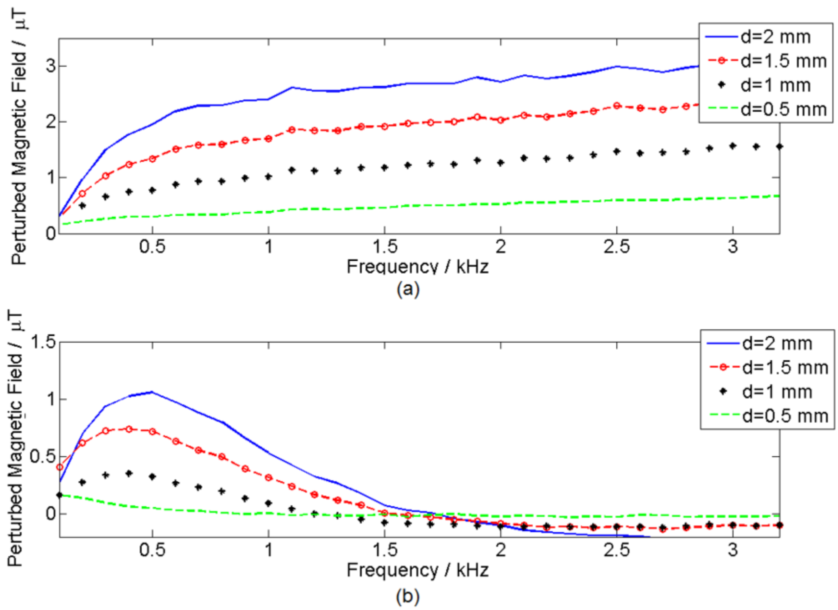

Figure 6. Magnitude of the perturbed magnetic field (Bx): (a) Surface Cracks with different depths (d=2 mm, d= 1.5 mm, d=1 mm, d= 0.5 mm); (b) Sub-surface cracks with different depths depths (d=2 mm, d= 1.5 mm, d=1 mm, d= 0.5 mm);

From the results, it is evident that the depth of a crack is correlated with the curve of the spectral magnitude of B_x in the y-position of the crack. For both cases (surface and sub-surface cracks), the peaks values of the spectral magnitude of B_x increase with the increasing depth of a crack. For sub-surface cracks, the values of B_x are dominant in the lower frequency of the spectrum. For surface cracks, the perturbed magnetic field of B_x occurs for all frequencies of the spectrum, and a small decrease of the perturbed part occurs in the lower frequencies because the eddy currents are forced to flow at deeper levels, originating a lesser perturbation of the magnetic field due to the presence of a surface crack.

4. Conclusions

The constructed multi-frequency signal allowed the surface and the sub-surface detection of cracks with 8 mm in length and 0.5, 1, 1.5 and 2 mm of depth in an aluminum plate with 4 mm thickness. For this kind of multi-harmonic excitation, it is important to reduce the amplitude peak of the generated signal in order to decrease the possibility to saturate the output of the GMR sensor and the output of the instrumentation amplifier. The Shapiro-Rudin approach was well suited to limit the maximum instantaneous amplitude of the excitation signal. In the frequency domain, the results obtained by the GMR sensor clearly show the difference in the perturbed magnetic field B_x between a surface and a sub-surface crack of equal dimension. The number of tones and the chosen frequencies of test should be optimized for the thickness of the metallic plate under test. The final results also show that the crack depth is directly related with the peak value of B_x in the central position of the cracks.

Acknowledgment

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

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