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An experimental comparison of multi-frequency and chirp excitations for eddy current testing on thin defects

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ABSTRACT

Non-destructive evaluation of materials and structures is still a key issue in some industrial scenarios as the production process and the quality inspection. In the case of metallic materials, economic and implementation reasons push for the use of eddy current testing techniques. In the last years, the effort of the research activity is been focused on the development of eddy current measurement procedures capable of providing as much information as possible about the presence, the location and the geometrical characteristics of defects. To this aim, newer signals characterized by a wide spectral content able to penetrate in the different layers of the material under test are substituting the older sinusoidal excitation. Among these, multi-frequency and chirp represent two optimal candidates within the class of frequency domain-based signals. The former is characterized by the simultaneous presence of many sinusoidal tones, while the latter exhibits a constant envelope and an instantaneous frequency that increases or decreases with time. In literature many interesting papers dealing with both excitation types are reported but an experimental performance comparison on a number of real defects is missing. Moreover the comparisons are usually executed on single measurements collected in presence of a defect in the location corresponding to the highest defect signal. Even if this strategy allows the analysis of the defect signature in time and in frequency domain, from both experimental and practical point of view, this approach is extremely sensitive to noise and it could be also difficult to be applied in on-line or in-situ inspections. In this paper, the proposed comparison aims at highlighting the suitability of each considered excitation method with respect to the extraction of defects geometrical features. It is proposed to combine the various excitation signals with image processing: indeed by developing a proper 2D image procedure from 1D eddy-current data it is possible to improve the defect detection capability when difficult cases are experienced (such as annealed and small cracks) and to extract more accurate information about the defect's geometric characteristics. After the image processing application, the multi-tone and the chirp approaches are quantitatively compared by using an ad-hoc figure of merit.

1. Introduction

Many factors influence the success of the Eddy Current Non Destructive Testing (ECT) technique when the

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problem of detecting, locating, and identifying flaws in conductive material has to be faced [1]. Among them are: (i) variations in the electrical conductivity and in the magnetic permeability of the test piece, caused by structural changes such as grain structure, work hardening, heat treatment and magnetization of the specimen; (ii) changes in lift-off or fill factor resulting from probe wobble, uneven surfaces, and eccentricity of tubes caused by faulty manufacture or damage; (iii) the presence of surface defects such as cracks, and subsurface defects such as voids and non-metallic inclusions; (iv) dimensional changes, such as thinning of tube walls due to corrosion, deposition of metal deposits or sludge, and the effects of denting; (v) the presence of supports, walls, and brackets and the presence of discontinuities such as edges.

To increase the sensitivity and the robustness of ECT, deep innovations in probes design, signal processing, and excitation signals optimization have been introduced during the last decade. As far as the excitation signals are concerned, many researchers are engaging the development of eddy current excitations able to provide as much information as possible about the presence, the location, and the geometrical characteristics of defects: signals characterized by a wide spectral content able to penetrate in the different layers of the material under test are gradually substituting the classical sinusoidal excitation approaches using either single frequency or multiple frequencies at different times.

Generally, the excitation signals can be divided in two categories corresponding to the time and frequency domain representations of these signals. The former has important representatives in pulsed (PEC) [2–5] or pseudo-noise excitations [6,7], while the latter proposes signals as the Multi-Frequency (MF-ECT) [8–10] and chirp one [11,12]. Pulsed signals are typically analyzed in the time-domain signal processing, while MF-ECT and chirp signals are instead analyzed by the use of transformed domains as the Fourier and the Chirplet.

Each one of these considered excitation signals presents advantages and disadvantages that prevent the election of an absolute best excitation signal. Time-domain techniques exhibit an inherently multi-frequency broadband nature and a great penetration due to the easiness of exciting eddy-currents in a continuous range of frequencies $f \in (0, f_0]$ even with signals significantly shorter than $T_0 = (f_0)^{-1}$. Moreover it is well known that by analyzing some features of the time signals such as the time-to-peak, the peak height, the zero-crossing point and the lift-off point of intersection, it is possible to locate discontinuities and to evaluate their depth and dimensions [13,14]. However the time-domain features are quite sensitive to noise and require calibration data for accomplishing the defect characterization task. To mitigate the effect of noise, and also to avoid calibration, several signal processing techniques for time signals from PEC have been developed. For instance features extraction by Principal Component Analysis revealed a useful tool for defect classification [15,16].

Differently form PEC, frequency domain signals are more demanding in their physical realization but they allow the exciting tones that compose the signal to be selected and at the same time they offer simpler signal processing to extract the wanted information about the presence and the characteristics of the defect.

The authors are investigating the field of Non-Destructive ECT for many years, proposing probes, measurement methods and excitation strategies to optimize the defect characterization by ECT methods [6,7,9,10,12,17–19]. Currently their research activity focuses on the use of signals in the frequency domain with the aim to improve the sensitivity of defect detection in some particular application fields, and especially for small and sub-superficial cracks.

In this paper they present a comparison of different excitation strategies for the assessment of the above-mention characteristics of thin cracks in conductive materials. In particular, the paper proposes an experimental approach based on the definition and analysis of a suitable figure of merit related to the detection capability.

2. Theoretical background

2.1. Basics of ECT

In ECT techniques a variable magnetic field $B_{ext}(t)$ is generated by a coil or an electro-magnet placed near the surface of the Sample-Under-Inspection (SUT). Under this excitation, the SUT reacts by producing a secondary magnetic field $B_{eddy}(t)$ for the presence of eddy currents in it. By applying proper measurement strategies, this secondary field can be measured with high accuracy. Two main approaches have been used so far in ECT applications: the first one in chronological order makes use of a coil to pick up the variations due to the secondary field by measuring its flux over the coil (quite often is the same excitation coil that is used also as receiver and its impedance variation is measured), the second one employs magnetic field sensors such as Hall or Giant Magneto Resistance (GMR) probes to directly measure the total magnetic field $B_{ext}(t) + B_{eddy}(t)$ in the proximity of the SUT surface [17–20]. The ECT relies on the fact that for samples composed of an homogeneous conductive and not-ferromagnetic material, as the Aluminum here considered, if edge effects can be disregarded, $B_{eddy}(t)$ does not change if the electromagnet is simply translated over the SUT; on the contrary, when the electromagnet is moved over a region of the SUT in which there is a discontinuity, an inclusion or a void, the spatial distribution of the eddy currents changes and, as a consequence, the secondary magnetic field changes too. By analyzing the variation $\Delta B_{eddy}(t)$ of the secondary field due to a defect (that can be a discontinuity, a void, a crack, and so on), some information about the nature and the geometric characteristics of the inhomogeneity can be inferred, such as the depth with respect to the inspection surface, the equivalent volume, the electrical conductivity, etc. In general, in order to achieve a high accuracy in the reconstruction of the defects characteristics, several measurements must be collected at different excitation frequencies and at different positions over the SUT, and advanced data processing algorithms must be implemented such as deterministic inversion procedures or comparisons with database of numerically simulated and