Electromagnetic Attenuation Factor Based NDE Approach for Depth Detection of Hidden Defects Using HTS rf-SQUID

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***Abstract*— We present a new approach for non-destructive evaluation (NDE) in homogeneous and isotropic metallic objects which contain defects at unknown depths based on single scan and multi frequency excitation. As known, there is an optimum frequency for each depth of defect. Finding the depth of an unknown defect requires us to find the optimal frequency. In conventional single frequency methods, the optimal frequency is obtained by applying a wide range of frequencies to the system separately and comparing the corresponding results in a time-consuming process. Conventional multi frequency inspections were introduced to obtain more information about test specimens. There are two ways to apply multiple excitation frequencies to the test sample. First way is to apply them sequentially to a single excitation coil which is still time consuming and the second method is to apply them simultaneously to multiple coils. In simultaneous excitation the testing time is shorter, but its processing of phase and amplitude signals is still challenging. We propose and examine the capability of the multi frequency eddy current (MFEC) method to detect the depth of hidden cracks in a shorter time period; using our HTS SQUID gradiometer-based system. The measurements are performed in a noisy environment, and a planar double-D shaped printed-circuit-board coil is used as the excitation coil. Comparing with the results of the consecutive single frequency excitation measurements, the obtained depths of the flaws using MFEC method was confirmed.**

Keywords*— *Depth Detection, Eddy current, SQUID sensor, multi frequency method, Nondestructive testing

I. Introduction

Nondestructive testing (NDT) is used widely to inspect and control the quality of materials without any contact between the sample and the sensor [1]. One of the most important goals of NDT is detection and characterization of hidden defects [1]. Eddy current testing is one of the NDT method which is induced within conductor by a changing magnetic field [2]. The ac current passing through the excitation coil is the producer of ac magnetic field. Defect detection can be optimized by choosing the optimum excitation frequency of ac current [2]. there is an optimal frequency for each penetration depth, which can be obtained from the skin effect formula as shown in (1) [4].

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}\sqrt{\sqrt{1+(\rho\omega\epsilon)^2}+\rho\omega\epsilon} \qquad (1)$$

In which $\rho, \mu, \epsilon, \omega, \delta$ are resistivity (Ω.m), magnetic permeability (H.m^{-1}), permittivity (F.m^{-1}) of the conductor, angular frequency (rad.s^{-1}) of current and penetration depth (m) respectively [4]. The basis of our non-destructive evaluation (NDE) system is the changes in the magnetic flux density (MFD) while scanning a sample due to its defects. Our samples are aluminum plates with different thicknesses and the defects are simple cracks with 1mm width and 200mm length and 5mm heights in different depths, as shown in Fig. 1. By replacing the parameters of aluminum conductor in (1), the relationship between penetration depth and frequency is simplified as (2).

$$\delta \cong \frac{0.0845}{\sqrt{f}} \qquad (2)$$

In the deeper parts of a sample, the electromagnetic (EM) radiation is more attenuated. Because the greater distances the EM wave travels, the more energy is transformed into internal energy of the medium [5, 6]. If the optimal frequencies for two penetration depths of δ_1 and δ_2 ($\delta_1 < \delta_2$) are equal to f_1 and f_2 respectively, then we expect to have the output of our system as it is shown in Fig. 2. Regards to more attenuation of the EM radiation in the depth of δ_2 in comparison to δ_1, the optimum amplitude of the output signal in the frequency of f_2 (A_2), should be less than corresponding value at the frequency of f_1 (A_1). We call the ratio of $\alpha \equiv A_2/A_1$ the attenuation factor for distance of $\Delta\delta = \delta_2 - \delta_1$ in our samples.

Examining the depth of a hidden defect requires us to find the optimal frequency in which the amplitude of the output signal of our system reaches its maximum value [3]. For this purpose, first the output signal must be recorded in a wide range of frequencies. And then the optimal frequency would be obtained by comparing the corresponding outcomes which is a time-consuming job [3, 6].

Inside a homogeneous and isotropic medium, Maxwell's equation is linear [7] and consequently, the principle of superposition for applying more than one frequency to the NDE system is true [8]. Applying more than one frequency to the NDE system speeds up the depth detection process, because the information from several frequencies can be obtained simultaneously [9].

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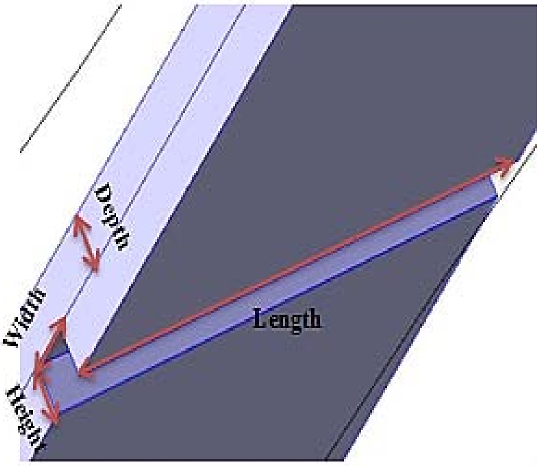

Fig. 1. The properties of a simple crack.

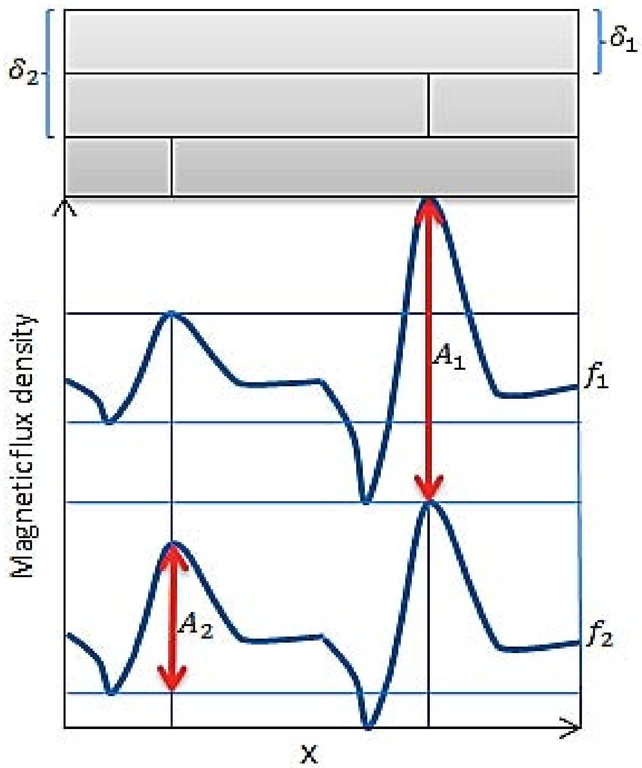

Fig. 2. The expected output signals of our NDE system in optimal frequencies of f_1 and f_2.

In this paper, the first aim is to find the attenuation factor of EM radiation, for a particular $\Delta\delta$, in our samples, and the second aim is to present multi frequency eddy current (MFEC) approach to detect the depth of hidden flaws in a shorter time.

II. SYSTEM SETUP

Out setup is described in detail in [6]. In brief, a high-Tc YBCO RF-SQUID (superconducting quantum interference device) gradiometer with a flux noise below $100\mu\emptyset_0/\sqrt{Hz}$ at 100 Hz is chosen as the magnetic sensor to examine the small changes in magnetic field in unshielded environments, in our NDE system [10]. Its characteristics are shown in table 1 [3].

TABLE I. CHARACTERISTICS OF SQUID

Baseline length	Diameter of washer areas	Coupled LC resonator frequency
1.5 mm	1.5 mm	750 MHz

A nonmagnetic scanning robot to scan one or two dimensions is used to assess samples [3, 10]. Other important parts of our system are a liquid nitrogen dewar to keep the SQUID gradiometer in it during the tests, a planar double-D shaped coil with 3cm diameter as the excitation coil which is mounted under the dewar and is driven by an ac current of 500 mA (rms), a lock in amplifier for amplification and extraction of desired frequency signals, and other excitation and data acquisition subsystems [10-13]. A general view of our NDE system is shown in Fig. 3 [6].

III. ATTENUATION FACTOR IN TESTED SAMPLE

A simple crack with known properties as mentioned in the introduction is hidden in the depth of 0.5cm in an aluminum sample. The optimal frequency of this known defect is obtained from (2) and equals to 285.61Hz. We have applied a sinusoidal current with this optimal frequency to the system and obtained the output signal while scanning the sample in one direction.

The corresponding result is shown in Fig. 4. The same test was done for a similar defect in the depth of 0.9cm in frequency of 88.15Hz which is its optimal frequency (Fig. 5). The peak to peak values of the curves in Fig. 4 and Fig. 5 are 0.4739 and 0.1761 respectively. According to the definition of attenuation coefficient as presented in the introduction, the attenuation factor in our tested sample for $\Delta\delta = 4mm$ is obtained $\alpha \cong 0.3716$.

Having the attenuation factor of a sample, one can easily find the depth of other possible unknown flaws using MFEC method which is described in the next section.

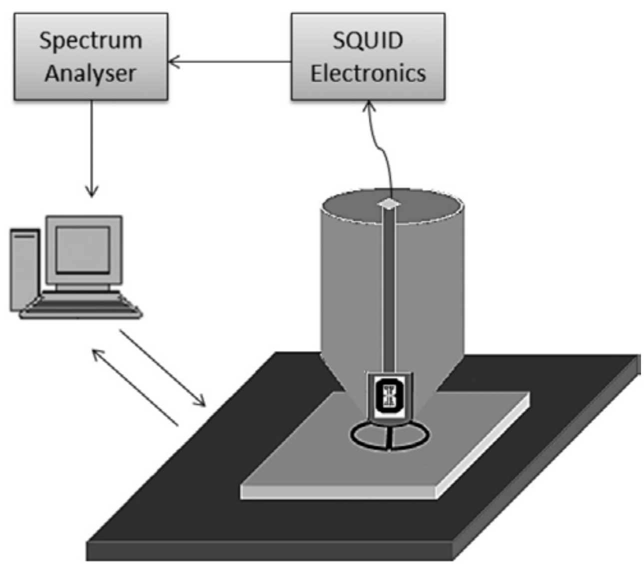

Fig. 3. A general view of our SQUID based NDE system [6].

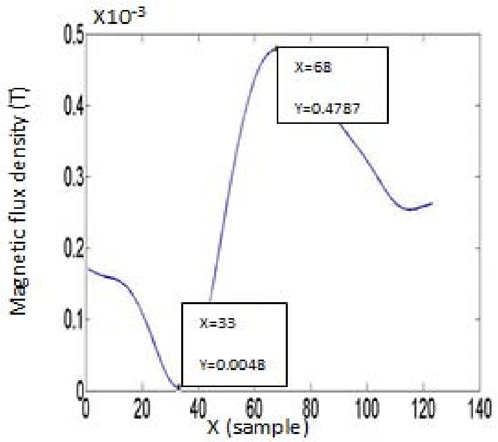

Fig. 4. The changes of MFD while scanning a sample containing a simple crack in 0.5cm depth in its optimal frequency.

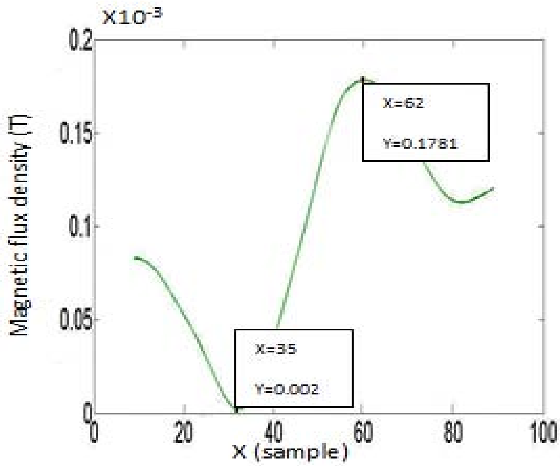

Fig. 5. The changes of MFD while scanning a sample containing a simple crack in 0.9cm depth in its optimal frequency.

IV. MULTI FREQUENCY EDDY CURRENT INSPECTION

In a homogenous and isotropic medium which the superposition principle for Maxwell's equation is true, applying more than one frequency to the NDE system is possible [6]. Consequently, the optimal frequency of an unknown defect can be found at a shorter time period, by applying a group of frequencies at the same time to the NDE system. This method is called MFEC method in which by applying multiple frequencies to the system, the magnetic flux density is measured in the output.

As we know, at the optimum frequency of each depth, the peak to peak value of the output reaches to its maximum. in this method, Firstly, we apply a multifrequency excitation to a sample with known attenuation factor and unknown flaws. Next, we find the peak to peak amplitude of the magnetic flux density for each frequency, using MATLAB. Finally, we calculate the depth of the unknown flaws, using the calculated attenuation factor. For example, assuming the attenuation factor of the tested sample is calculated using the same approach as shown in part III ($\alpha = 0.3716, \Delta\delta = 4mm,\ A_1 = 0.4739, A_2 = 0.1761$).

Using MFEC method, if we apply several frequencies to the system and find the peak to peak values of the output for each frequency (for example B_1, B_2, B_3 in Fig. 6). Moreover, assuming the maximum value among the measured peak to peak values, is B_2 corresponding to f_2. Using the attenuation factor of the sample, we can calculate the depth of the unknown depth as (3).

$$h = \frac{B_2}{A_1} \times \frac{\Delta\delta}{\alpha} = B_2 \times \frac{\Delta\delta}{A_2} = B_2 \times \frac{4mm}{0.1761} = 22.71 \times B_2\ (mm) \quad (3)$$

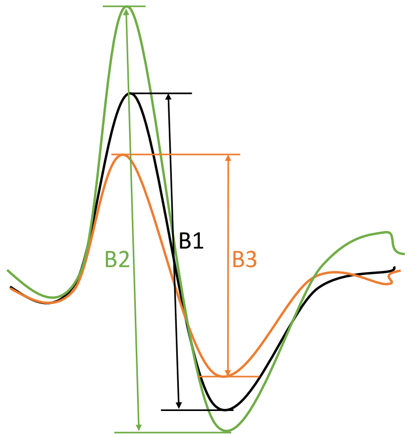

Fig. 6. Example of magnetic flux densities for multifrequency excitation of a sample with an unknown hidden defect.

V. CONCLUSION AND SUMMERY

A new approach for depth detection of unknown hidden defects in homogenous and isotropic samples was proposed. In this approach we apply multi frequency eddy current method to the NDE system and obtain the attenuation factor of EM waves for a particular penetration depth difference in our samples. Using the calculated attenuation factor, we are able to calculate the depth of unknown hidden defects as presented in MFEC inspection section of this paper. In other words, after applying multi frequency excitation to the sample, by using MATLAB the peak to peak amplitude of the magnetic flux density for each frequency is obtained and by using the calculated attenuation factor, we are able to calculate the depth of the unknown flaws.

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