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Evaluation of transient eddy current oscillations response for thickness measurement of stainless steel plate

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ABSTRACT

Detection of a wall thickness change in pipelines is extremely important to avoid unwanted leakages and accident reduction in industrial structures. In the present study, transient eddy current oscillation (TECO) nondestructive testing (NDT) method has been used to detect the thickness of stainless specimen. Damped free running oscillations that are generated by cyclic exchange of energy between a capacitor and an induction coil in the TECO probe, are used to induce the eddy currents into the test specimen. The resultant magnetic field is detected by using a Hall sensor in the vicinity of the test specimen. The experimental results are analyzed in the frequency domain by calculating the power spectral density (PSD) of the detected decay of oscillations response from the probe. Two features, peak frequency and −3 dB bandwidth of the PSD, are used to interpret the thickness variation in test specimen. The TECO method has been successfully applied to measure the thickness of stainless steel plates.

1. Introduction

The methods of nondestructive testing (NDT) ensure the integrity of the industrial structures without disturbing structure's functionality. The industrial structures such as pipelines in oil–natural gas, thermal and nuclear power industries are often operated in harsh environmental conditions [1]. The structural deterioration of industrial structures and their subsequent failure are complex processes, which are affected by many issues like, static factors such as material, size, duration in use (age), and dynamic factors such as climate and internal pressure. A change in wall thickness due to corrosion in industrial structures has been an un-avoidable problem and is one of the leading causes to pipeline failures [2]. A leakage in pipelines causes unwanted outages, enormous economic losses and sometimes catastrophic failures. Thus, continuous monitoring of structures for lifetime assessment is always an important issue to be addressed in industries.

There are several technologies including non-destructive testing (NDT) inspection and advanced sensor techniques for condition monitoring of industrial structures. Some of the most used NDT methods are eddy current testing (ECT), ultrasonic testing (UT) and radiography testing (RT) [3–5]. Electromagnetic testing methods, like ECT have various advantages such as being noncontact techniques, that don't require a coupling agent (as needed in the UT) and not hazardous as RT. Therefore, the electromagnetic methods became popular and are a frequent choice for the engineers to inspect metallic structures [6]. Some of the electromagnetic testing methods are eddy current testing (ECT), multi-frequency eddy current (MEC), remote field eddy current (RFEC), magnetic flux leakage (MFL) and pulsed eddy current (PEC) [7–11]. Electromagnetic testing methods are based on Faraday's law of electromagnetic induction [12]. In ECT, a time varying excitation current generates a time varying magnetic field that creates eddy currents in the test object. By measuring the resultant magnetic field one gets information about the physical condition of the test object. This magnetic field response can be measured by solid state magnetic field sensors such as giant magneto-resistance (GMR) and Hall-effect sensors [13,14]. Many important developments in solid state magnetic field sensors occurred during the past 50 years [15], especially in size reduction of the sensor chip and a higher sensitivity in the wide-frequency range starting from DC to 1 M Hz. Therefore, ECT integrated with sensor technology has developed increasingly in the testing of materials since the 1950s, especially in the nuclear and aircraft industries [16,17]. The present study employs a Hall sensor for the detection of the magnetic field because the magnetic field is not so weak to require a higher sensitivity sensor and also because the Hall sensors have a very linear response to the external magnetic field, and require simple electronics.

Eddy current based techniques can be applied to detect defects, corrosion and to measure the thickness of metallic structures.

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Important advantages can be pointed out to these methods as their capacity of detection through coating and the fact that only little pre-cleaning is required, thus reduced testing time. MFL method has been in use for the detection of corrosion pits and wall thickness measurements [18] and RFECT is being in use for the detection of defects in high pressure feeder water heaters in nuclear plants [19]. Recently, pulsed eddy currents with a square wave excitation received an extreme interest in applications such as the detection of defects and wall thickness measurements [20]. Nevertheless, ECT have their own disadvantages like its limited skin depth and heating of excitation coil due to operating longer times at higher excitation of currents. MFL is good at detection of surface and near surface defects and mostly applicable to the ferromagnetic materials. In RFECT, it is required a highly skilled person to analyze the obtained remote field component and directly induced components. Whereas the PEC requires high current pulses with sharp rise time to attain broad band of frequencies in excitation, thus this method requires expensive equipment not only in the excitation part, but also in the data acquisition as high-speed sampling rates are required.

This paper presents an experimental study on transient eddy current oscillations (TECO) method [21]. In contrast to conventional ECT that uses continuous sine wave excitation or PEC that uses short current pulses, TECO method uses free running damped oscillations to create eddy currents in the metallic material under test. The TECO probe includes an induction coil and a capacitor, which are connected in parallel. A DC source charges the capacitor and supplies current to the coil. When the probe circuit is opened, the transient of the excitation current is a damped oscillation regime. These free running oscillations are used to induce eddy currents into the test specimen beneath the probe.

Our previous papers report the TECO response on the specimen thickness measurements using time domain features, such as decay time and zero crossing [21]. As the TECO method is still considered as new approach for the thickness measurements, this paper intends to be a step forward looking for further features that can address the test material thickness measurement. In this paper the detected magnetic field response is analyzed in the frequency domain using power spectral density (PSD). Usually most of the information in a signal is carried by its irregular shapes and its transient phenomena. Finding of small fluctuations in the time-domain is somewhat a difficult task. These difficulties can be overcome by transformation into the frequency domain [22]. Recent advancements in computer programming and large memory handling capability, data analysis became easier and more acquainted to the researchers to analyze data in different domains using transformations. Different frequency domain transforms like Fourier transform (FFT) and wavelet transform (WT) were frequently applied for the data analysis. For instance, wavelet-transform used for de-noising the eddy current signals and for the defect classification using PEC signals [23,24]. In the present study, two different features, −3 dB bandwidth and peak frequency of PSD, have been identified and used for the thickness measurement of stainless steel plates.

As the TECO method operates in free running oscillatory regime, there are some positive aspects that can be mentioned about this method. The TECO method has advantages like low power consumption and coil heating can be avoided. Low speed and low cost DAQ can be employed due to a slow decay of oscillations within a limited bandwidth. TECO setup has simple electronics, thus more compact and inexpensive systems can be used.

2. Experimental setup

The experimental setup of TECO inspection system is represented in Fig. 1. It includes a probe, a function generator (for switching control), an instrumentation amplifier, a data acquisition system and a personal computer. The probe consists of a capacitor (0.56 μF) and an excitation coil of inductance 1.5 mH (250 turns of 0.3 mm copper wire) connected in parallel with a DC power supply through a switch. The DC power supply used to drive the probe with 700 mA of current while the switch is ON. The function generator generates the positive pulses to control ON and OFF states of the switch with a 30% duty cycle (to avoid unnecessary heating of coil) at a repetition rate of 2 s. Coil in the probe was mounted in a cup type ferrite core to get more concentrated and focused field [25].

A Hall sensor was placed inside the excitation pancake coil at the bottom side at the cylindrical axis center to detect the magnetic field which is perpendicular to the surface of the test specimen, as shown in the 3D design of the probe in Fig. 1. A current sampling resistor R (0.2 Ω) was connected in series with the coil. A differential amplifier circuit was designed using INA 118 instrumentation amplifier to amplify the Hall sensor output voltage with the gain factor of 200. A NI-6251 data acquisition (DAQ) system was interfaced to the computer using Lab VIEW software to acquire the experimental data at a sampling rate of 1 MS/s.

When the switch between the probe and the DC power supply is open, an exchange of energy occurs between the capacitor and the coil for certain time. The oscillations that are created due to this physical phenomenon were used to induce the eddy currents into the test object beneath the coil. The resultant magnetic field is detected by using a Hall sensor to determine the physical condition of the test material. It is well known that the Hall sensor output voltage is proportional to the external magnetic field which is perpendicular to its sensing area. The maximum thickness of test specimen used in the present study is 4 mm. The value of capacitance C was chosen carefully to generate damped free running oscillations of the excitation current with a frequency around 5.5 kHz. For thickness measurement studies, it is very important to consider that the thickness of the test specimen being measured should be at least 3/4 of the standard depth of penetration of eddy currents [26]. The frequency chosen in this study has standard depth of penetration of the induced currents of about 6 mm in a homogeneous SS304 specimen, which covers the entire range of the maximum thickness of the test specimen used in this study.

3. Results and discussion

To test the feasibility of the TECO method, a homogeneous stainless steel (SS304) test specimens with different thickness of 1, 1.5, 2, 3 and 4 mm were prepared for the experimental study. Measurements were taken with the probe placed on the test specimen. The Hall sensor response has been recorded immediately

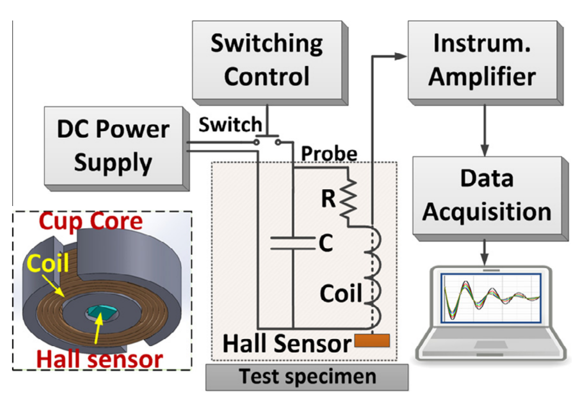

Fig. 1. Block diagram of the experimental setup and 3D design of the probe.