ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 18(3), 342-347 (2013)
http://dx.doi.org/10.4283/JMAG.2013.18.3.342

Review paper: Application of the Pulsed Eddy Current Technique to Inspect Pipelines of Nuclear Plants

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(Received 31 May 2012, Received in final form 7 October 2012, Accepted 9 October 2012)

Local wall thinning in pipelines affects the structural integrity of industries, such as nuclear power plants (NPPs). In the present study, a development of pulsed eddy current (PEC) technology that detects the wall thinning of pipelines covered with insulation is reviewed. The methods and experimental results, which have two kinds of probe with a single and double core, were compared. For this purpose, the single and double core probes having one and two excitation coils have been devised, and the differential probe with two Hall sensors has been fabricated to measure the wall thinning in insulated pipelines. The test sample is a stainless steel having different thickness, laminated by plastic insulation to simulate the pipelines in NPPs. The excitation coils in the probe is driven by a rectangular current pulse, the difference of two Hall sensors has been measured as a resultant PEC signal. The peak value of the detected signal is used to describe the wall thinning. The double core probe has better performance to detect the wall thinning covered with insulation; the single core probe can detect the wall thinning up to an insulation thickness of 18 mm, whereas the double probe can detect up to 25 mm. The results show that the double core PEC probe has the potential to detect the wall thinning in an insulated pipeline of the NPPs

Keywords : Pulsed eddy current (PEC), single core probe, double core probe, wall thinning, insulation

1. Introduction

The pipelines of power plants and heat exchangers are covered with a thermal insulator in order to decrease the heat loss. During long-term services, corrosion might occur on the outer side of the pipe as corrosion under insulation (CUI) [1], or on the inner side of the pipe as flow accelerated corrosion (FAC) [2]. Wall thinning of pipelines can develop, which may finally results in a catastrophic failure. Therefore, local wall thinning is a point of concern in almost all steel structures, such as pipelines, particularly pipelines which are covered with a thermal insulator made of materials having low thermal conductivity (fiberglass or mineral wool). Hence, the NDT methods which are capable of detecting wall thinning and defects without removing the insulation are necessary. There are several noncontact electromagnetic NDT methods in use, such as the eddy current technique (ECT) [3, 4]. Although ECT has gained wide acceptance in NDT, this technique suffers from a limited depth of penetration [5]. The pulsed eddy current (PEC) technique uses repetitive pulses having a short duration in time instead of a sinusoidal wave with a single frequency. A pulsed excitation generates numerous frequencies simultaneously in the work piece [6]. The PEC technique offers an alternative to these conventional techniques due to its potential advantages, such as less susceptible to interference, less power consumption because of using short pulses which are more desirable specification in the development of portable instruments. The conventional ECT which operates with a single frequency sinusoidal excitation has gained wide acceptance in the field of NDT [7]; yet, this techni-

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This paper was presented at the ICM2012, Busan, Korea, July 8-13, 2012.

que suffers from a limitation, i.e., penetration depth or skin depth. The skin depth equation is given by $\delta = \sqrt{1/\pi\mu\sigma f}$, where μ is the permeability, σ is the conductivity and f is the frequency of excitation, and the penetration depth δ depends on excitation frequency f [8]. In contrast to the traditional ECT, the PEC employs a nonsinusoidal excitation, such as a pulse or square wave, instead of a single frequency sinusoidal excitation. Because the Fourier transform of a pulse contains multiple frequency components [9, 10], a rectangular pulse can provide the depth profile of a material under test [11, 12]. The usage of short current pulse excitation reduces the power consumption, which is the most desired specification in the development of portable instruments. Due to the potential advantages of the PEC, prevalent investigations on this technique have been conducted, such as detection of wall thinning and corrosion in aircraft multilayer structures [13, 14]. On the other hand, many parts of the pipelines in nuclear power plants are welded with a dissimilar metal. The PEC techniques are expected to detect the defects in the dissimilar weld part. The fundamental of PEC testing has been studied extensively with regards to the conducting plate using analytical and numerical methods [15, 16]. Analytical expression for transient induction voltage of receiving coil created by the pulsed eddy current induced by a transmitting coil over a conducting plate was presented elsewhere [17]. PEC testing has been applied to pipeline inspection by some leading inspection companies [18, 19]. The present research describes the application of PEC for wall thinning or corrosion as well as for subsurface defects. To apply the PEC technology in the pipeline inspection of nuclear power plants, PEC probe having a driving coil with a Hall sensor, pulse amplifier and a real time data acquisition program were developed for the continuous monitoring of the obtained signal. Usually, the PEC probe consists of an excitation coil to induce the eddy currents in the metal structure, which is a detecting sensor to measure the perturbed magnetic field. In our PEC probe, an exciting coil in conjunction with a Hall sensor has been used. Two different types of probe having a single excitation coil with a Hall sensor, a differential probe having an excitation coil with two Hall sensors, and a dual core differential probe having two excitation coils with two Hall sensors have been constructed and compared for the detection of wall thinning in pipelines without removing the insulation. The PEC response to varying metal thickness was measured at various thicknesses of insulations on the tested sample. Excitation coil in the probe is driven by a rectangular current pulse; the time domain features of the detected pulse were used to describe the wall thinning in the tested sample. A real time LabVIEW program was developed for data acquisition and scanning the probe on the insulated sample. The scanning results were continuously displayed on the computer monitor.

2. Development of PEC System

2.1. PEC system and differential probe

The PEC system consists of a pulse amplifier, a probe having a driving coil with a magnetic field detecting sensor (Hall sensor), a sensitive differential amplifier with variable gain to amplify the output voltage from the Hall sensor, A/D converter, X-Y scanner and a computer with signal processing software, as shown in Fig. 1. The rectangular signal from the waveform generator is fed to a pulse amplifier, which excites the excitation coil in the probe. A LabVIEW-based data acquisition program was developed to continuously monitor the variation in the thickness of the sample and was observed on the computer screen in a specified thickness monitoring window. Fig. 2 shows the front panel controls of the program. The time domain feature, which is the peak value of the detected pulse, is used for the scanning test in order to monitor the variation in the thickness of the tested sample. The PEC probe was scanned on the flat side of

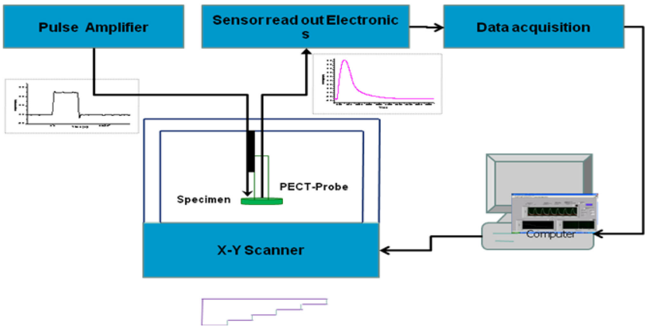
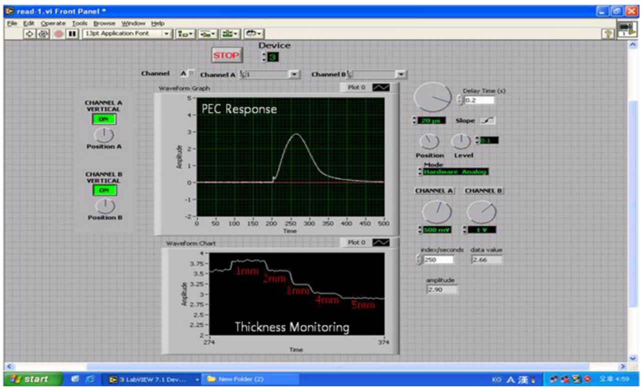


Fig. 1. (Color online) Block diagram of the PEC system.


read-1.vi Front Panel *

Device 3

Channel A

Delay Time (s) 0.2

20 μs

Mode Hardware Analog

CHANNEL A 500 mV

CHANNEL B 1 V

index/seconds 250

data value 2.66

amplitude 2.90

Fig. 2. (Color online) Front panel controls of the PEC system.

Table 1. Differential Hall sensor probe configuration.

Single core		Double core	
Number Of Turns	120	Number Of Turns (Coil 1&2)	150
Coil Gauge	0.5	Coil Gauge	0.5
Coil Inner Diameter	22 mm	Coil Inner Diameter	27 mm
Coil Outer Diameter	26 mm	Coil Outer Diameter	35 mm
Coil Height	10 mm	Coil Height	10 mm
Coil Current	500 mA	Coil Current	1A
Excited Pulse Width	500 ms	Excited Pulse Width	2 ms

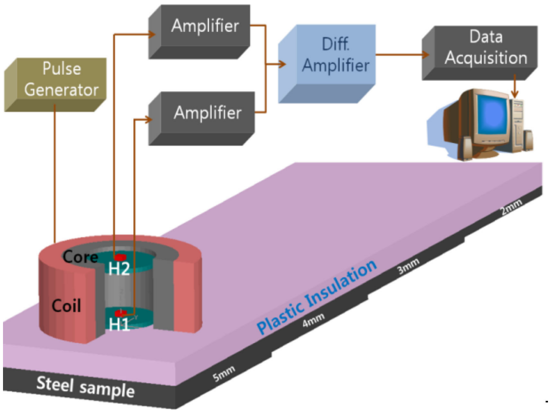


Fig. 3. (Color online) Configuration of single core probe and connection of differential probe.

the tested sample, which includes the plastic insulation. The intensity chart on the front panel shows the change in the thickness of the sample in terms of color variation according to the detected differential pulse amplitude. The exciting signal frequency and duty cycle can be adjusted by the waveform generator depending on the necessity. The PEC probe characteristics are determined by a combination of measuring environments, such as induced current, insulation thickness and sample thickness. The single and double probe configurations are shown in Table 1.

A proper PEC probe has to be devised according to the sample configuration and size in order to achieve the optimum signal. The sensor probe consists of an excitation copper coil wounded on a cylindrical ferrite core. To compare the probe performance, two kinds of probes having a single and double core are tested with regard to the same sample. To detect the PEC response, two Hall-sensors (H1 and H2) are placed at the bottom and top axial centers of the excitation probe, respectively

3. Results and Discussions

3.1. Single core probe and probe response

The single core differential probe consists of an excitation copper coil of 120 turns wound on a cylindrical ferrite core. It has a 22 mm inner and a 26 mm outer diameter. The excitation coil in the probe has been driven by the pulse amplifier. To detect the PEC response, two Hall sensors, H1 and H2, are placed at the top and bottom axial center of the excitation probe, as illustrated in Fig. 3. The excitation coil is driven by a current pulse of 500 mA, 500 μs width. When the probe is mounted on the conducting sample, the exciting pulse causes induced currents within the sample to flow in the direction where its self flux opposes the externally imposed flux (Lenz's law); the ohmic dissipation engenders the induced currents to decay exponentially with time [20]. The magnetic field detected by the two sensors is subtracted by a difference amplifier, and the resultant signal is used as the probe signal. The calibration sample is a stainless steel with a thickness variation from 1 mm to 5 mm. A plastic plate having 8 mm thickness is attached on the flat side of the samples to represent the thermal insulation of the pipelines, as demonstrated in Fig. 3. During the measurement, the PEC probe is placed on the plastic insulation. Fig. 4 shows the response of individual Hall sensors as well as the differential signal (V_{diff} = H2 – H1). When the probe is in air, the responses from H1, H2 are almost the same; therefore, the difference is nearly zero. Now by mounting the probe on the insulated sample, the induced voltage from H1 slowly increases than H2 to reach its maximum value because the Hall sensor H1 is nearer to the sample surface; hence, the effect of the induced eddy currents are

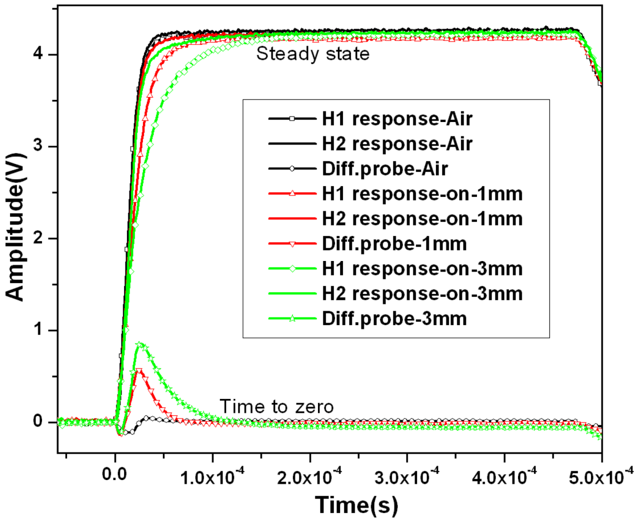


Fig. 4. (Color online) Response from individual Hall sensors H1 and H2 in the probe and differential signal when the probe is in air and on an insulated sample.

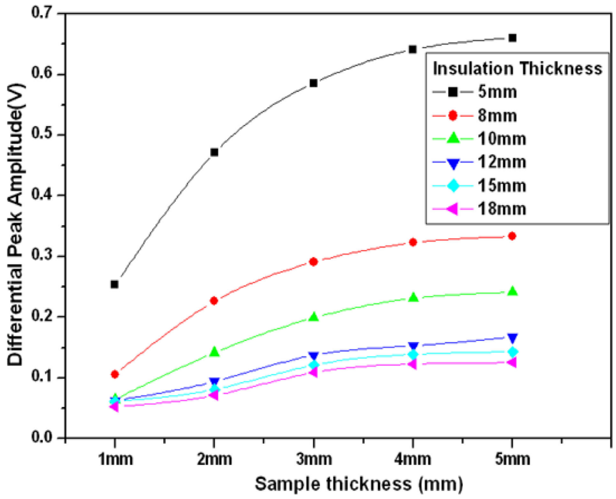


Fig. 5. (Color online) The peak value of the detected pulse as a function of sample thickness at different thickness insulations.

more on H1 than H2. If there is an increase in the sample thickness (3 mm), then the induced voltage from H1 increases at more slower rate to reach its steady state value due to the large cross sectional conducting area which leads to higher induced eddy currents [21]. Therefore, if the sample thickens increases, the raise time of H1 to its steady state value also increases so that the differential amplitude i.e. the difference of two Hall sensors responses (H2-H1) increases in proportionate to the sample thickness. When the two Hall sensor responses approach their steady value then differential signal becomes zero this portion of the signal is termed as 'time to zero' this measure also can be used to explain the thickness change, from Fig. 4 it is clear that the time to zero increases with increasing the sample thickness. Fig. 5 shows the results which are measured at 5, 8, 10, 12, 15 and 18 mm of insulations on the tested sample. As the thickness of the sample increases, the peak value of the pulse is increased. The time-domain feature, such as the peak value of the detected pulse, is used to interpret the thickness of the test sample.

3.2. Double core probe and probe response

The double core probe consisted of two excitation copper coils with 150 turns wound on cylindrical ferrite cores with dimensions of 24 mm inner and 28 mm outer diameter. The two coils, which are wound on ferrite cores, are connected electrically in series and physically placed side by side with a small gap between them. A plastic plate was laminated on the flat side of the sample to simulate the insulation of the pipelines. Fig. 6 shows the dual-core differential PEC probe design and the insulated steel sample. Two Hall-sensors (H1 and H2) are placed between the two excitation coils at the top and bottom sides in order to detect the PEC response. The probe geometry and field distribution was simulated by using ANSOFT Maxwell [22] simulation software. Fig. 7 conveys the simulated magnetic field distribution of the differential probe (simulated with sinusoidal excitation). The magnetic fields detected by the two sensors were subtracted using the difference amplifier (AD620), and the resultant signal was used as the probe signal. The calibration sample was a stainless steel (SS304) sample with a thickness ranging from 1 mm to 5 mm [23].

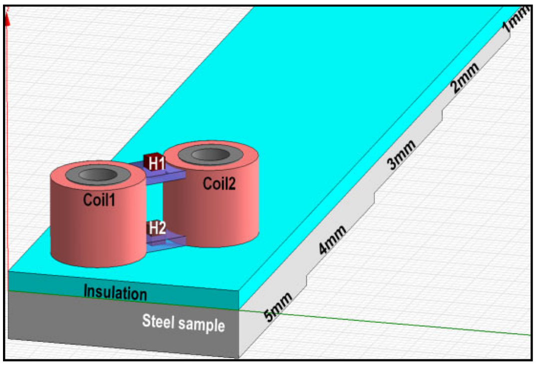


Fig. 6. (Color online) Dual-core differential PEC probe design and insulated steel sample [25].

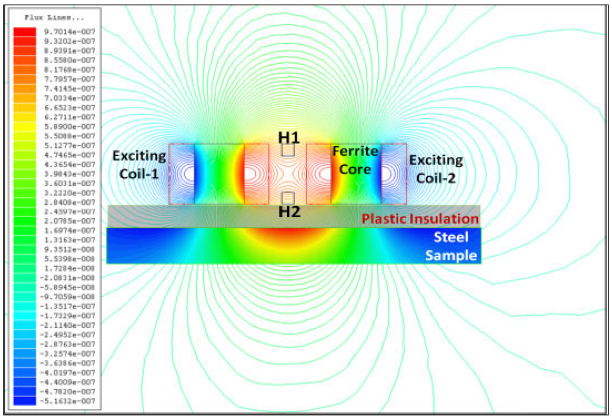


Fig. 7. (Color online) The magnetic field distribution of a differential probe simulated with the ANSOFT Maxwell simulation software [25].

The excitation coil was driven by a rectangular pulse with 2 ms width and 1A current. When we bring the probe into the proximity of the conducting test sample, due to the pulse excitation, the responses from Hall sensor1 (H1) and Hall sensor2 (H2) can be explained as follows: the initial steeper part of the exciting pulse induces eddy currents in the test sample (higher rate of change of voltage induces eddy currents). The field of the induced eddy

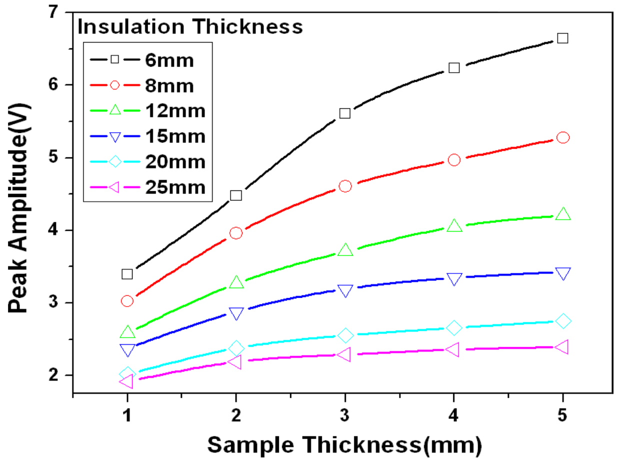


Fig. 8. (Color online) The pulse amplitude as a function of sample thickness at different thickness of insulations [25].

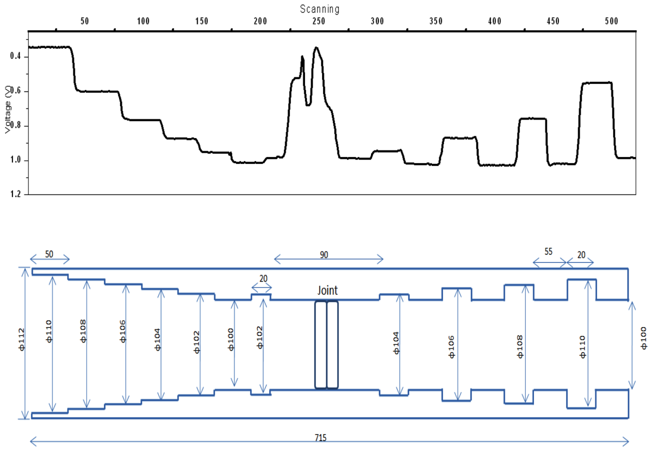


Fig. 9. (Color online) The measured signal from double core probe at a distance of 25 mm from the simulated wall thinned pipe surface.

currents counteracts with the exciting coil's magnetic field; when the exciting pulse reaches the flat response (there is no rate of change in the exciting voltage), then the induced eddy currents exponentially decay to zero due to the electrical resistance of the specimen under test. Hence, when the probe is placed on the conducting plate, the detected field rises slowly and exponentially to its steady state value [24]. Fig. 8 shows the pulse peak amplitude versus sample thickness measured by the double core probe at a different thickness of insulation on the test sample. The tested sample is insulated with different insulations with thicknesses of 6, 8, 12, 15, 20 and 25 mm. The PEC response to varying metal thicknesses was measured using the differential probe. The time-domain feature, such as the peak value of the detected pulse, is used to interpret the thickness of the test sample. As we are measuring the difference of the two sensors' responses, the difference signal V_{diff} has an amplitude increase; thus, the differential pulse peak value increases as the specimen thickness increases. Compared to the results of the single core probe in Fig. 5, the double core probe can detect the wall thinned sample covered with a thicker insulator. Fig. 9 shows the measured signal from the double core probe at a distance of 25 mm from the sample surface [25]. The lower part of the figure is the simulated pipe sample with wall thinning and defects, and the upper part of this figure represents the Hall sensor signal response of this sample. If there is an increase in the thickness of the test sample under the probe, the large cross sectional conduction area leads to higher induced eddy currents [26]. Therefore, the induced signal from the differential Hall sensor well describes the configuration of pipe defects.

4. Conclusion

The PEC technique which detects the wall thinning of pipelines covered with thick insulation using a single and double core PEC probe has been reviewed. A differential probe which was used in the PEC system has been fabricated for the detection of defects in an insulated stainless steel pipe. The probe performance was tested using the wall thinning of the calibration sample and simulated wall thinning pipe under different thickness of insulations up to 25 mm. The time domain features of the detected pulse, such as pulse amplitude and time to zero, were used to detect the defects. The scanning results were displayed on the computer monitor. The results indicate that the dual core differential PEC technique indicates the best performance among a single Hall sensor, differential Hall sensor and dual core differential probe. A dual core differential probe can detect the wall thinned sample under more thick insulation compared to the single and differential Hall sensor probe. The scanning results were successfully displayed with an intensity chart on the computer monitor. The results reveal that the dual core differential PEC probe shows better performance compared to the single core probe in detecting the wall thinning of insulated pipelines.

Acknowledgement

This work was developed by the research project on the development of advanced diagnostic technique for micro-material degradation and damages, as a part of a long-term nuclear R&D program supported by the Ministry of Education, Science and Technology (MEST), Korea.

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