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Optimization of Design Parameters of Pulsed Eddy Current Probe for Displacement Measurement for finding Diametrical Creep of Test Specimen Capsules

T.V. Shyam[1,2], Archanna Sharma[2], Ankur Kaushik[3], I.V. Dulera[3], S.K. Sinha[1], Nirupam Das[1] and Germain Court[4]

[1]Reactor Engineering Division, Bhabha Atomic Research Centre, Trombay-400085, Mumbai, India.
[2]Homi Bhabha National Institute, Anushakti Nagar-400094, Mumbai, India.
[3]High Temperature Reactor Section, Bhabha Atomic Research Centre. Trombay-400085 Mumbai, India.
[4]Commissariat à l'énergie atomique et aux énergies alternatives (CEA), France.

(Corresponding author: T.V. Shyam)
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ABSTRACT: The online diametrical creep measurement of test specimen capsules, subjected to hostile conditions like high temperature, is being proposed using pulsed eddy current testing technique. The two pulsed eddy current probes are kept diametrically opposite to the test specimen capsule. The pulsed eddy current testing is a broad band technique, where early part of the signal carries surface features of the test specimen and later part of the signal carries depth features of the test specimen. Lift off point of intersection (LOI) is a signal feature exhibited by pulsed eddy current testing probe having send pick up coil configuration. When the lift off, the gap between the probe face and the test specimen is varied, all the signal traces intersect at a common point called lift off point of intersection. The slope of the signals at LOI have a correlation with the gap between the probe face and the test specimen. The paper discusses about the design of probe using electromagnetic simulation software in terms of optimization of number of winding turns of send coil and pick up coil, amplitude and pulse width of current through send coil, rate of rise of current through send coil.

Keywords: Pulsed eddy current, Lift off point of intersection, creep.

Abbreviations: LOI, Lift off point of intersection; PEC, Pulsed Eddy Current; LVDT, Linear Variable Differential Transformer; GUI, Graphical user Interface.

I. INTRODUCTION

For studying the material properties of the futuristic metal alloys for their application in high temperature reactors, it is required to carry out experiments with specimens of these metal alloys in high temperature and irradiation environment with capability to monitor on line geometric changes. In one such proposed experiments, it is also required to measure biaxial strain in test specimens which are in the form of capsules having outer diameter of 10mm. For this type of experiments one has to measure in axial direction of the sample as well as in the radial direction of the sample. The diametrical expansion of the capsule can be measured by positioning non intrusive displacement sensors at two fixed locations which are at diametrically opposite sides of the capsule. The sensor can be either capacitive type or electromagnetic based type. The experiments proposed to carry out in in-pile with sample carrier tubes having inner diameter of the order of 24 mm. This restrains the height of the sensor to the order of 5mm to get accommodated in the sample carrier.

For employing electromagnetic methodology for non intrusive displacement or gap measurement between the sensor face and the test specimen eddy current based sensor is proposed. The conventional eddy current sensor is based on exciting the sensor with harmonic test frequency and observe the output on complex impedance plane display which plots inductive inductance versus real resistance [7-8]. The conventional eddy current testing is multi parameter sensitive technique. With single frequency excitation only two test variables can be distinguishable or separable. Much more advanced technique like Pulsed Eddy Current (PEC) technique can give more information about the test specimen due to broad band nature of the excitation [9]. The pulsed eddy current technique bombards the test specimen with broad spectrum of frequencies of electromagnetic waves. The higher frequencies are attenuated at the surface of the test specimen due to skin effect. Where as the lower frequencies penetrate deep into specimen. The earlier part of the signal depict the surface features of the test specimen and deeper features of the test specimen are represented in the trailing part of the signal. Fig. 1 shows the schematic of typical pulsed eddy current testing setup.

The test specimen capsule to be tested is to be placed in the test pile having high temperature hostile conditions. The online creep measurement is proposed to be measured using pulsed eddy current technique. The two pulsed eddy current probes are configured in diametrically opposite positions. The primary coils of the probes are connected in series addition configuration for pulsed current excitation.

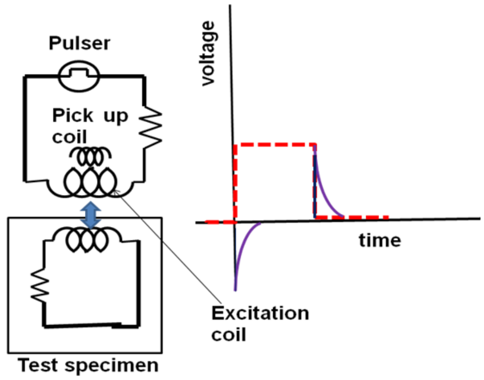

Fig. 1. The schematic of typical pulsed eddy current testing setup.

The pickup coil voltages can be signal processed independently to derive the lift off or gap of the probe with respect to the the test specimen. The measurement of respective lift off of each probe can realize the diametrical creep. The schematic of experimental setup for pulsed eddy current probe based test setup for diametrical creep measurement is shown in Fig. 2. The signals acquired can be acquired in PXI based high data acquisition. The slope of the signals at the Lift off point of Intersection can be calibrated and correlated to the lift off parameter.

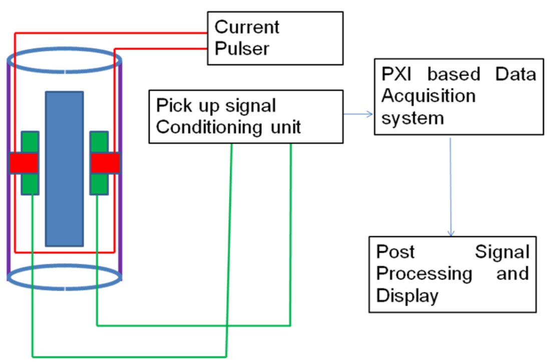

Fig. 2. Schematic of experimental setup for pulsed eddy current probe based test setup for diametrical creep measurement.

II. RELEVANCE OF LIFT OFF POINT OF INTERSECTION (LOI)

Lift-off term in eddy current testing terminology is defined as the gap between the eddy current sensor face and the test specimen. The lift off is generally a sensitive eddy current testing parameter which has a strong bearing on the measurement of other eddy current testing parameters like electrical conductivity and thickness of the test specimen. Similarly lift off measurement is affected by a lesser degree by the other eddy current parameters like electrical conductivity and the thickness of the test specimen. The Fig. 3 depicts the lift off measurement.

The unique phenomenon observed in pulsed eddy current technique is the lift off point of intersection where signal traces intersect at a common point by varying the lift off parameter. This Lift Off point of Intersection (LOI) is an interesting feature of the pulse current signals. Much literature has been written on this feature [1]. The LOI feature has importance while measuring the parameters other than lift off as the lift off effect remains invariant at LOI. The Fig. 4 depicts typical response signals with different lift off conditions.

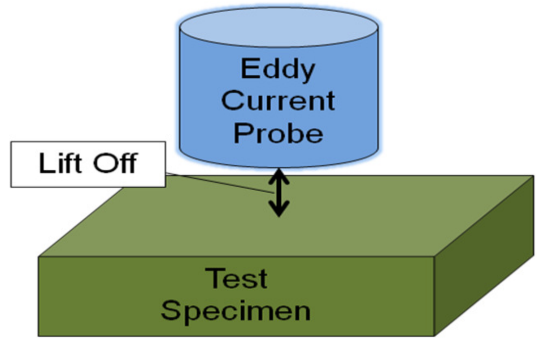

Fig. 3. Schematic showing conceptual lift off measurement.

III. OTHER TECHNIQUES FOR CREEP MEASUREMENT

Creep measurement of specimens having 23 mm inner diameter, using six nozzle air gauge is reported to be done in NRU reactor [2]. Idaho National Laboratory has reported work on use of LVDT (Linear Variable Differential Transformer) based instrumented creep test rig [3]. It is reported Diameter Gauge has been used for in-pile measurements by Idaho National Laboratory (INL) for in-pile measurements for assessing cladding creep [4]. The diameter gauge is based on LVDT-based technology. It consists of two sets of primary excitation coils and secondary pickup coils wound adjacent on a ferritic bobbin with mirror symmetry. It is reported in the Siloette reactor of the Centre de Grenoble du CEA, strain relaxation measurement of a helicoidal spring specimen in axial direction was carried out with Resonant cavity method [5]. Creep measurement based on low frequency, square configuration potential drop measurements suitable for high temperature and high pressure power station components has been reported [6].

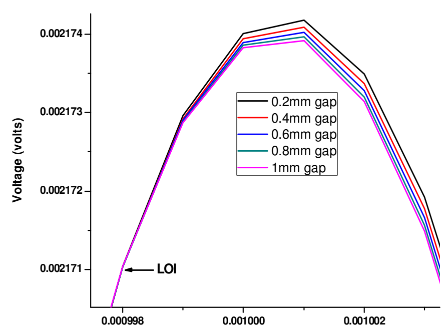

Fig. 4. Schematic showing typical pickup signals for varying lift off conditions.

IV. ELECTROMAGNETIC MODELING OF THE GAP SENSOR

The gap sensor was modeled for computation of voltage in the pick up coil. The pick up voltages were calculated for various gap settings between the probe face and the test specimen. The test specimen is set to have a disc shape. The send and pickup coils were circular in shape having rectangular cross section. The send coil and pick up coil are placed concentric with each other. The axes of the coils are perpendicular to the face of the disc shaped test specimen. The geometry model is shown in Fig. 5. The send coil is set to carry a constant current pulse with 16 ampere current and having pulse width time of 1 milli second. The parametric study with various conditions of gap between the test specimen and send coil and pick up coil assembly were carried out. The Magnetic Field mode in the AC/DC module of the COMSOL Multiphysics was used for the electromagnetic modeling. The voltage pick up was computed using the time dependent or transient solver of COMSOL Multiphysics package.

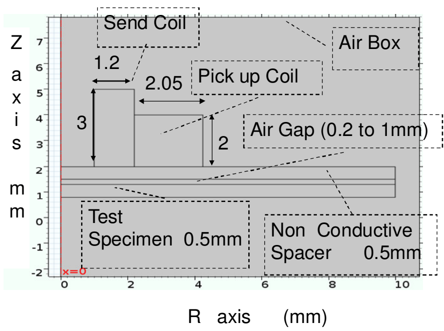

Fig. 5. Axi- symmetric Geometry model of the gap sensor (All dimensions in mm).

In COMSOL Graphical user Interface (GUI), a rectangular function was defined for the type of excitation function of the send coil with pulse width parameters. In Geometry node, the send coil geometry, the pick up coil geometry, the test specimen geometry was defined. The air gap between the test specimen and the send coil and pick up coil assembly was defined. For achieving the parameterization of the air gap from 0 mm to 1mm range in steps of 0.2 mm, the dimensions of the send coil, pickup coil and the air gap geometry in terms of height variable were manipulated during different steps of parameterization. All the geometries drawn are enclosed in closed air box for defining the domain limits for the computation of the equation. From Material library node, appropriate materials were selected for the primary coil, pick up coil, test specimen, air gap and air box. Copper was selected as the material for both the coils. Steel SS 316 as the material for the test specimen. The electrical conductivity of steel SS 316 was set to 1.3514×10^6 S/m and relative permeability 1.005. Air was chosen for air gap, air box and non conductive spacer. In Physics node settings is made for magnetic field physics node. The basic physics Eqns. (1) to (4) for computation in the node are as follows

$$\nabla \times H = J \quad (1)$$

$$B = \nabla \times A \quad (2)$$

$$J = \sigma E + \sigma v \times B + J_e \quad (3)$$

$$E = -\frac{\partial A}{\partial t} \quad (4)$$

where 'H' is the Magnetic Field intensity.
'J' is the total current density.
'B' is the magnetic flux induction density.
'E' is the Electric Field strength.
'σ' is the electrical conductivity.
'v' is the velocity term.
'j_e' is the external current density.
'A' is the magnetic vector potential.

Multi turn coil configuration setting is assigned to send coil and pick up coil. The send coil is driven by 16 ampere pulsed current by employing rectangular function. The send coil is set wound by 34 SWG with 70 turns. The pick up coil is set to wound by 34 SWG with 50 turns. Meshing was set to have finer mesh for send, pick up coil and test specimen. The air gap between the test specimen and the send and pick up coil assembly was set to have custom setting with mesh size of 0.6mm as maximum size and 0.00022 mm as minimum size. For computation of the study of the problem, parametric study was set for varying the gap between the test specimen and the send and pick up coil assembly. The gap was varied in steps of 0.2mm from 0mm to 1 mm. Time dependent solver was selected for computation. After computation, in post processing module the voltage induced in the pick up coil was evaluated in global evaluation node. The induced current density is shown in the Fig. 6.

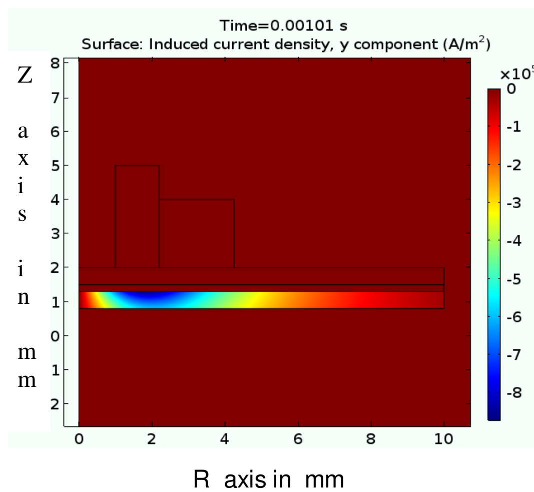

Fig. 6. Induced current density in the test specimen.

V. OPTIMIZATION OF NUMBERS OF TURNS OF SEND COIL AND PICK UP COIL

For finding out optimized combination of number of turns of send and pick up coils, probe configuration having different set of number of turns for send and pick up coils were tested out.

Table 1: Configuration of pulsed eddy current testing probes.

S. No.	Number of turns in Send coil	Number of turns in pick up coil
1.	70 turns	15 turns
2.	70 turns	50 turns
3.	40 turns	50 turns
4.	48 turns	32 turns
5.	35 turns	25 turns
6.	35 turns	50 turns
7.	10 turns	15 turns
8.	20 turns	15 turns

The results of different case studies is shown below. The excitation current was set 16 amperes. The excitation pulse width was 1 millisecond. Fig. 7 shows the slope comparison for case studies between pulsed eddy current probes having different set of configuration each having different set of number of turns for send and pick up coils and probe configuration is shown in Table 1. The parametric study of slopes versus gap variation for the configuration having 10 turns in send coil and 15 turns in pick up coil is shown in Fig. 8.

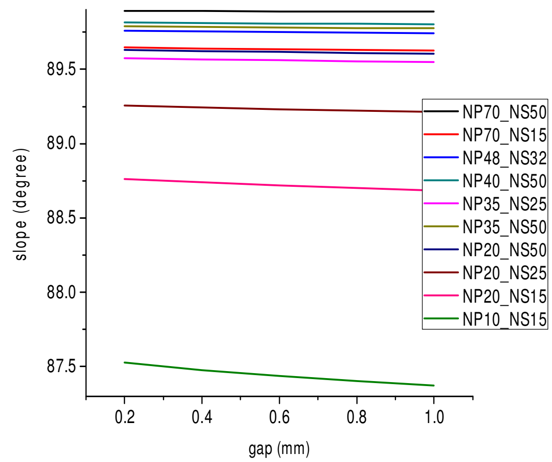

Fig. 7. Slope comparison derived after simulating pulsed eddy current probes having different set of configuration each having different set of number of turns for send and pick up coils and probe configuration.

From the plots it was noticed that the phenomenon of Lift off point of Intersection is observable. At Lift off point of Intersection the slopes of the signal plots change with gap variation between the test specimen and the primary and pick up coil assembly. Simulation results show that slope angle versus gap variation curves have higher sensitivity with less number of send coil turns and pick up coil turns.

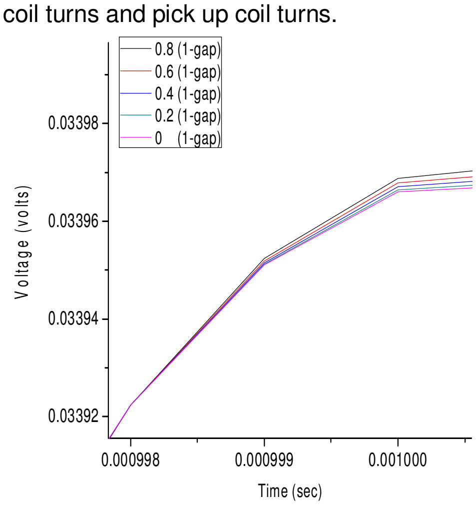

Fig. 8. Parametric study of the voltage induced in the pick up coil versus gap variation of pulsed eddy current probe having 10 turns Send coil turns and 15 turns pick up coil turns.

But pickup voltage in the pick up coil reduces with less number of turns. In juxtaposition, there is a limit to reduce the number of turns for send coil and pick up coil, as parasitic capacitance and inductance of the lead wires will dominate over impedance of the send coil and pick up coil. It requires to provide pre-amplifier to boost the signals. This may not be a viable option in hostile environment and as well as having constricted space.

VI. OPTIMIZATION OF AMPLITUDE EXCITATION CURRENT TO PULSED EDDY CURRENT PROBE

For finding out optimized amplitude of excitation current, two PEC probes having configuration of 10 turns for Send coil and 15 turns for pick up coil and second probe having 48 turns for Send coil and 32 turns for pickup coil were modeled. Currents ranging from 30 amps to 0.1 amps was set as excitation current. The excitation pulse width was 1 millisecond. The electromagnetic modeling was carried out for 30 amperes, 20 amperes, 10 amperes, 5 amperes, 1 ampere, 0.5 ampere and 0.1 ampere. The results PEC probes having configuration of 10turns for Send coil and 15 turns for pick up coil are shown in Fig. 9.

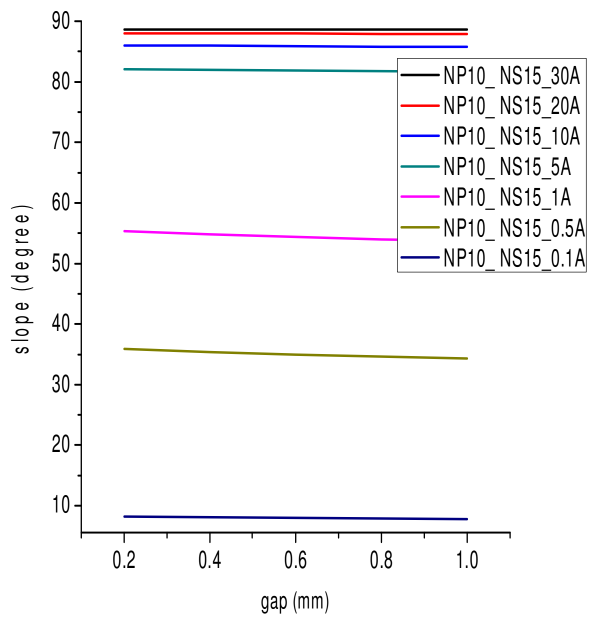

Fig. 9. Parametric study of amplitude of current excitation with PEC probe having configuration of 10turns for Send coil and 15 turns for pick up coil.

The results PEC probes having configuration of 48 turns for Send coil and 32 turns for pick up coil are shown in Fig. 10. For probe having 10 turns Send coil turns and 15 turns pick up coil turns when excited with 1 ampere excitation pulse has shown higher sensitivity. For probe having 48 turns Send coil turns and 32 turns pick up coil turns when excited with 0.1 ampere excitation pulse has shown higher sensitivity. For the case of probe having 10 turns Send coil turns and 15 turns pick up coil turns, the eddy current density becomes too small to produce sufficient slope angle sensitivity for excitation current amplitudes less than 1 ampere. Where as the case for probe having 48 turns

Send coil turns and 32 turns pick up coil turns, higher number of turns of send coil and pick up coil produce higher eddy current density even at 0.1 ampere excitation amplitude and generate sufficient slope angle sensitivity.

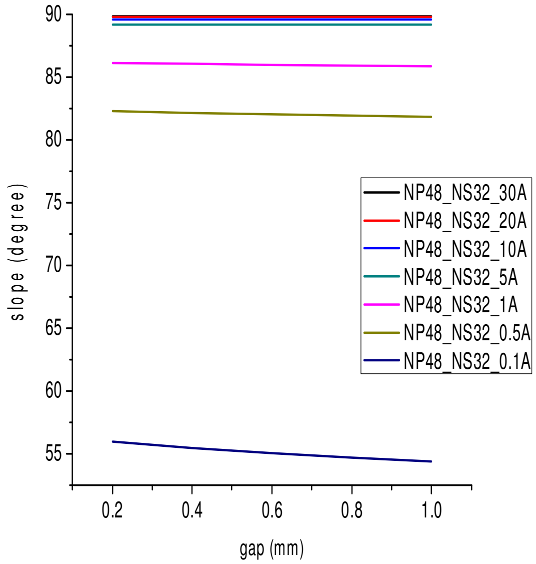

Fig. 10. Parametric study of amplitude of current excitation with PEC probe having configuration of 48 turns for Send coil and 32 turns for pick up coil.

VII. OPTIMIZATION OF PULSE WIDTH DURATION TO PULSED EDDY CURRENT PROBE

For finding out optimized pulse width of excitation current , two probe configuration having 10 turns send coil turns and 15 turns pick up coil turns and second probe having 48 turns send coil turns and 32 turns pick up coil turns were modeled. Excitation current was set for 1 ampere.

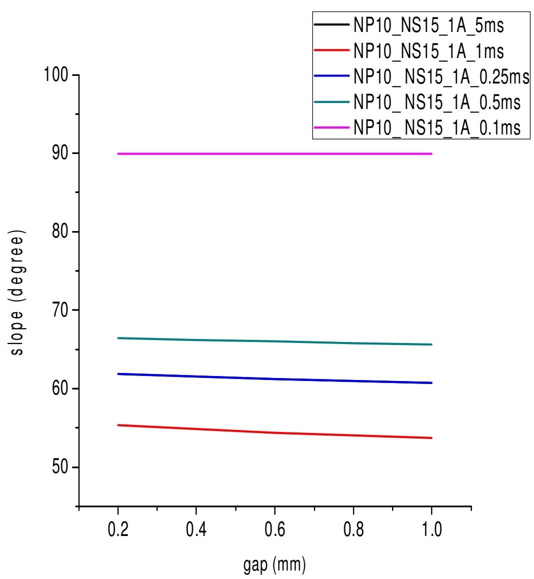

Fig. 11. Parametric study of pulse width of current excitation with PEC probe having configuration of 10turns for Send coil and 15 turns for pick up coil.

The excitation pulse width were set 5 milliseconds, 1 millisecond, 0.5 millisecond, 0.25 millisecond and 0.1 millisecond. The results of PEC probe having 10 turns Send coil turns and 15 turns pick up coil turns is shown in Fig. 11. The results of PEC probe having 48 turns Send coil turns and 32 turns pick coil turns is shown in Fig. 12. For both the cases of a) probe having 10turns Send coil turns and 15 turns pick up coil turns and b) probe having 48 turns Send coil turns and 32 turns pick up coil turns it was observed that excitation current pulse having around 1 millisecond pulse width shows better slope angle sensitivity. Lower pulse width of current produce dominant higher frequency components. Higher frequency components produce higher surface density on the test specimen. Thus higher slope angle sensitivity. However, there is a trade off as the rate of rise of current is limited by inherent inductance of the send coil.

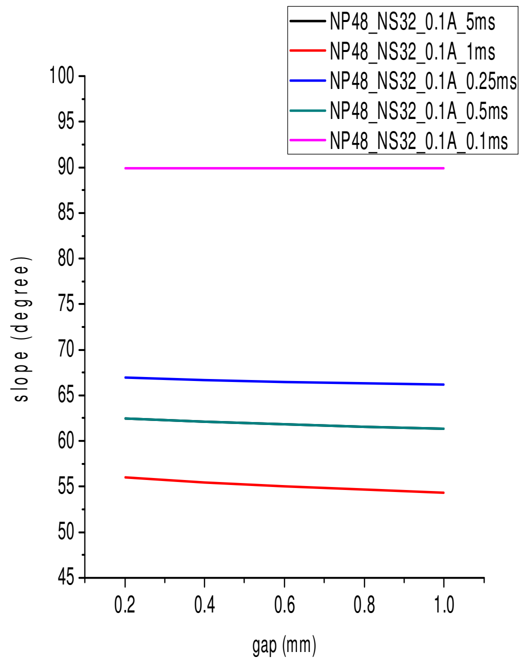

Fig. 12. Parametric study of pulse width of current excitation with PEC probe having configuration of 48 turns for Send coil and 32 turns for pick up coil.

VIII. STUDY OF RATE OF RISE OF CURRENT EXCITATION PULSE TO PULSED EDDY CURRENT PROBE

The effect of rate of rise of current excitation pulse was studied by electromagnetic modeling. The slope comparison of pulsed eddy current probe having 10 turns Send coil and 15 turns pick up coil with excitation current of 1 ampere was carried out for rate of change of current having smoothing factor of 0.0008 (0.0000636sec for 1 ampere step change in pulse amplitude) and smoothing factor of 0.0002. The results are shown in Figs. 13 and 14. Higher slew rate of current produces higher slope angle sensitivity. Higher slew rate produces a higher amplitude for all frequency components in excitation pulse. This generates higher surface eddy current density and produces higher slope angle sensitivity.

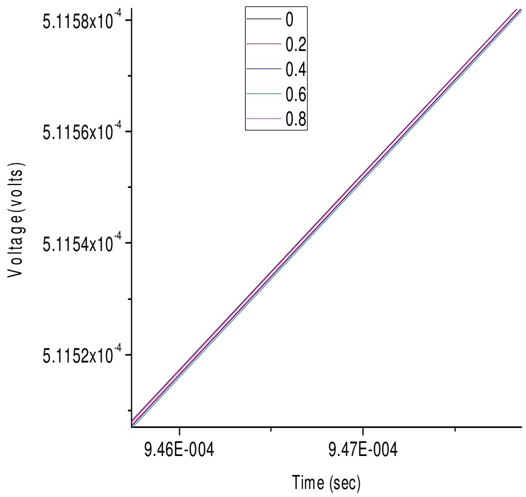

Fig. 13. Effect rate of change of current Smoothing factor (0.0008) 0.0000636sec for 1 ampere pulse amplitude for pulsed eddy current probes having 10 turns Send coil turns and 15 turns pick up coil turns and pulse width 5 milli seconds.

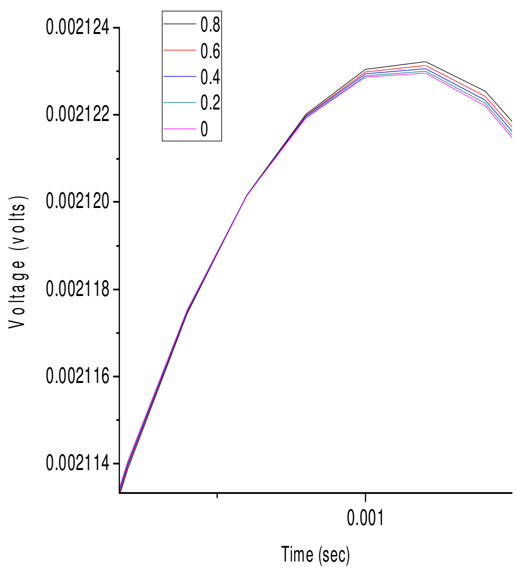

Fig. 14. Effect rate of change of current Smoothing factor (0.0002) 0.00001 sec for 1 ampere pulse amplitude for pulsed eddy current probes having 10turns Send coil turns and 15 turns pick up coil turns and pulse width 5 milli seconds

IX. CONCLUSION

The number of turns for send coil and pick up coil of the PEC probe were optimized. The observation was that the slope angle sensitivity versus gap variation increases with less number of send coil turns and pick up coil turns. At the same time pickup voltage also reduces with less number of turns. There is a limit to reduce the number of turns for send coil and pick up coil, as parasitic capacitance and inductance of the lead wires will dominate over impedance of the send coil and pick up coil. Further pre-amplifier has to be connected to boost the signals. This option may not be possible for the case, where space constraints exists. The excitation current amplitude was optimized. It was observed that for probe having 10 turns Send coil turns and 15 turns pick up coil turns 1 ampere excitation pulse shown higher sensitivity. The eddy current density becomes too small to produce sufficient slope angle sensitivity for excitation current amplitudes less than 1 ampere. It was observed that for probe having 48 turns Send coil turns and 32 turns pick up coil turns 0.1 ampere excitation pulse shown higher sensitivity. Higher number of turns of send coil and pick up coil produce higher eddy current density even at 0.1 ampere excitation amplitude and generate sufficient slope angle sensitivity. The excitation current pulse width was optimized. It was observed that for probe having 10 turns send coil turns and 15 turns pick up coil turns and 48 turns send coil turns and 32 turns pick up coil turns around 1 millisecond pulse width shows better slope angle sensitivity. Lower pulse width of current produce higher frequency components. Higher frequency components produce higher surface eddy current density on the test specimen. Thus higher slope angle sensitivity. There is a trade off as the rate of rise of current is limited by inherent inductance of the send coil. The slew rate of excitation current pulse was optimized. It was observed that the higher slew rate of current produces higher slope angle sensitivity. The higher slew rate produces a higher amplitude for all frequency components in excitation pulse. This generates higher surface eddy current density and produces higher slope angle sensitivity. In the modeling factors like lead cable inductance and capacitance were not considered.

X. FUTURE SCOPE

Based on the modeling results, fabrication of the pulsed eddy current testing sensor and experimental trials will be carried out in mock setup. The effect of parasitic capacitance and inductance of the lead wires on the probe performance will be evaluated. Further performance tests will be planned to carried out in high temperature conditions.

Conflict of Interest. The above said published work is purely academic in nature carried out in BARC, India and is published without any intend to promote any commercial interests.

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