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Feeder Pipeline Wall Thickness Measurement Using Pulsed Eddy Current Technique

Suvadip Roy, T.V Shyam, B.S.V.G Sharma, S.K Pradhan
Atomic Energy Regulatory Board, Bhabha Atomic Research Centre

Abstract - In the present study a Pulsed Eddy Current based probe has been developed to monitor wall thinning of Feeder Pipelines is 200 MWe Indian PHWR's due to Flow Accelerated Corrosion. The sensor consists of an Excitation coil excited with Pulsed Current excitation and a coil Receiver internal to the Excitation coil. The optimization of the Sensor structure , geometry , coil properties, magnitude of excitation current have been performed by developing a model and solving it using a Finite Element Method (FEM) Simulation software. A Ferrite core has been used in the sensor to improve its response to the PEC signal. The resultant signal from the receiver coil is the PEC signal. The Decay coefficient (inverse of logarithm of Decay Rate) of the signal was correlated to thickness of the Carbon Steel Feeders. Moreover Time-Frequency analysis using Weigner Distribution was performed on samples of the Time-Domain signal to correlate the Time-Frequency zones sensitive to wall thinning of the Feeders. The experimental results have indicated that the proposed sensor has the potential to detect the wall thinning in Carbon Steel Feeder Pipes with a resolution of 300 microns.

Index Terms **– Flow Accelerated Corrosion (FAC), Pulsed Eddy Current Technique (PECT), Non-Destructive Testing (NDT), Pressurized Heavy water Reactor (PHWR).**

I. INTRODUCTION

Feeder pipelines in Pressurized Heavy Water Reactor (PHWR) which carry the coolant from the headers to the coolant channels as well as from the coolant channels to the steam generator suffer from Flow accelerated corrosion (FAC) majorly at the elbows of the pipelines[1]-[2] which being maximum at the outlet elbow. These feeders carry the coolant from the headers and as the headers are located at a fixed position so the feeder pipes need to have bends to accommodate these offset in order to enter the respective coolant channel. It is these bends and elbows which are susceptible to FAC. So it is required to propose a technique to find out the thickness of Feeder pipelines during In-Service-Inspection (ISI) to monitor effects of FAC. Earlier Ultrasonic technique was used but due to stringent surface preparation requirement as well as high man-rem consumption an alternative technique is proposed in this work. Non- Destructive Testing (NDT's) for specimens have been used from time immemorial. They are used to inspect and evaluate materials, parts and other products in ways that do not adversely affect their serviceability. As because the tests are non-destructive 100% inspection can be made to assure uniform quality of products for critical use. Among all the various NDT techniques available Eddy current testing has earned huge popularity in the past few decades. They have been used widely to detect flaws in conductive materials and also for various characteristics extractions of materials [3]-[6]. The conventional Eddy current testing uses single frequency sinusoidal coil excitation and the specific excitation frequency is selected depending on the permeability, conductivity and the depth of penetration of the specimen to be inspected [7]. But if the depth of penetration or the depth till which the specimen has to be examined to extract the characteristic parameters varies then it is better to go for a broad band technique most popularly called as '**Pulsed Eddy Current Technique'**. Here rather than using a single frequency sinusoidal excitation, a pulsed excitation is used where the Duty cycle and Frequency of the pulse can be selected as par the application is concerned [8]. The main advantage is that as we know if we use Fourier series expansion then the Pulse can be written as the sum of a fundamental Frequency and a series of higher order harmonics. As depth of penetration inside the material is a frequency dependent phenomenon and it isinversely proportional to the square root of the operating frequency so it can be concluded that the higher frequencies concentrate at lower depths and hence reflect or give surface properties whereas the lower frequencies penetrate to higher depths and give depth characteristics of materials [9]. Hence by using such a modified broad band technique it is possible to get both the surface as well as the depth related information without the need to change the probe or the operating frequency. Another advantage is that the amount of energy delivered per pulse is much higher than AC excitation. This provides a stronger measured response during and immediately after the pulse excitation. Power consumption is also less in PEC because of the pulse excitation [10]. Moreover Instrumentation is also much simpler than conventional Eddy current testing. In the present study a PEC based sensor has been designed consisting of an Excitation coil and an internal coil Receiver with a Ferrite core. The Decay coefficient of the signals is correlated with thickness of the Carbon Steel Feeders. Time – Frequency study of the received signal is also performed to correlate the Time-Frequency zone sensitive to thickness parameter. The work includes optimization of sensor parameters, geometry using FEM simulation software, fabrication of the sensor based on the optimized parameters, experimental validation and Time- frequency analysis of the signal to correlate with thickness.

II. SIMULATION STUDIES

For 220 MWe PHWR's there are four types of Feeders of size 32NB,40NB,50NB & 65NB with wall thickness

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varying between 5.5 -7.4mm[11] made up of Carbon Steel(CS) ASTM A-333 Gr.6.This is done to match the flow according to the power produced in each channel to obtain an uniform channel outlet temperature. Based on the specific application a surface probe was designed [12] as there was no way of accessing the internals of the Feeder Pipes during ISI, as Feeder Pipes carry the process fluid containing radioactivity. A 3-D model was developed using FEM software. The model was used to optimize properties like Outer Diameter of the Excitation Coil, Inner Diameter of the Excitation coil, Inner Diameter of the Receiver coil, Outer Diameter of Receiver coil ,Height of excitation and Receiver coil, magnitude of excitation current and dimensions of the Ferrite core[13] .Coarse Tetrahedral Meshing was used for the model with Boundary Layer mesh covering the entire thickness of the cylindrical specimen. The Ferrite core used for the model had a maximum permeability (μ) of 55 and conductivity (σ) of 0.02 Siemens. The following 3-D model was used for Simulation:

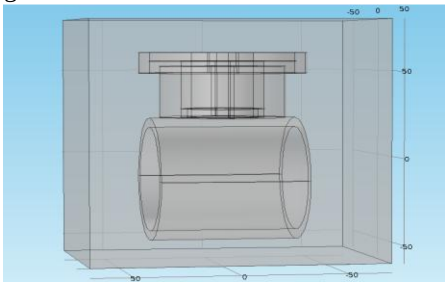

Fig. (1)- The 3-D Model of the Sensor on Cylindrical Specimen

The excitation waveform was the rect(t) function with an ideal switching time of 1.0E-6 sec and an on time of 10 ms.The peak value of excitation current was 10A with an average value of 100 mA. Eddy Current is produced on the specimen surface as an effect of induced voltage due to change in magnetic flux during transition from ON state to OFF state & vice versa of the Pulsed excitation waveform. The Voltage developed in the receiver coil is due to the net vector difference of the magnetic field of the Excitation coil and that due to the Magnetic field of the eddy current. It is seen that the voltage produced in the Receiver decays off when the pulse is switched off. The slope of the decay waveform is a function of the thickness of the specimen. By plotting logarithm of the received voltage against time the variation between two thicknesses can be easily found out. Decay Coefficient, inverse of the logarithm of the decay slope is defined which increase with thickness of the specimen. Moreover the effect of variation in Lift-off which is the distance between the Sensor and the test specimen on the received waveform was also studied. The above simulation model was designed for 65 NB CS Feeder pipeline whose thickness was varied to observe the change in the received waveform. The Magnetic Flux distribution on the specimen and the coil is given in the Fig.2 below :-

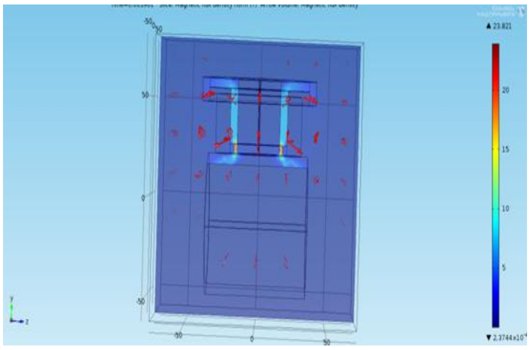

Fig. (2)– The Magnetic Flux Distribution

It is seen that the magnetic flux developed on the surface of specimen and in the coils vary with time. The data samples were taken from the simulation model for the received signal and the Logarithm of the received waveforms were plotted as a function of Time. The voltage waveform plotted against time is developed in the receiver coil due to Low to High transition of the excitation pulse which again decays off as the pulse remains in the High state. The slope of the decaying received voltage waveform varies as a function of thickness of specimen. The Decay coefficient defined as the inverse of logarithm of the Decay slope was scaled up by a factor of 100 and was plotted against thickness. It was observed that the Decay coefficients increase with thickness of Ferromagnetic CS test specimens. The Fig. is given below:-

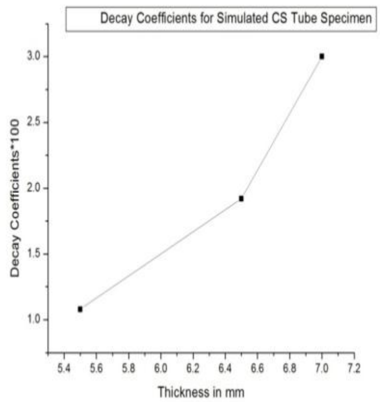

Fig. (3)– Decay Coefficient for Simulated Model with 65 NB Pipe

The effect of Lift-off i.e. the distance between the sensor and the specimen on the Decay coefficients were studied and was found out to be negligible upto 0.5mm gap between the sensor and test specimens but there was a change in peak amplitude of the signal which was found to decrease with increase in Lift-Off. But it was not an area of our concern as we were mainly concerned with slope of the decaying waveform which was approximately constant. Finally the optimized parameters of the sensor as found out from the simulation results are tabulated below:

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Table (I) the optimized characteristics of the Excitation and Receiver coil

Property	Excitation Coil	Receiver Coil
Outer Diameter(mm)	20	10
Inner Diameter(mm)	10	4
Height(mm)	30	10
Wire Gauge(SWG)	36	36
No Turns	4000	800
Resistance(Ω)	244	28
Inductance(mH)	86.931	2

The Inductance and Resistance were calculated by using empirical formulas which were functions of diameter of the wire used, N.O turns and resistance per unit length of the type of coil used. Resistance of coils was found for a specific coil by the formula:

R= Resistance per unit length * Length of the coil (L), Where the Length of the coil is found by the formula [7]

Length of coil (L) = 2 * π * r * N (mm) Where r is average radius of the coil and N is Number of turns of the coil

Secondly Inductance of the coils is found out by the following empirical relationship:

$$L(\mu H) = (0.8 * a^2 * N^2) / (6 * a + 9 * b + 10 * c)$$

Where a is average radius of the windings
b is Length of the solenoid

c is Difference between the outer & inner layer of the coil

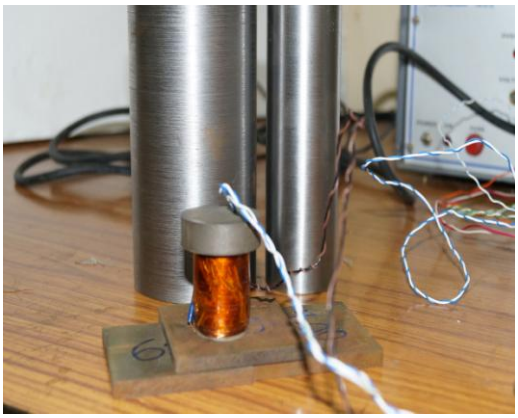

Fig. (4)–Actual Sensor Developed

III. EXPERIMENTAL SETUP

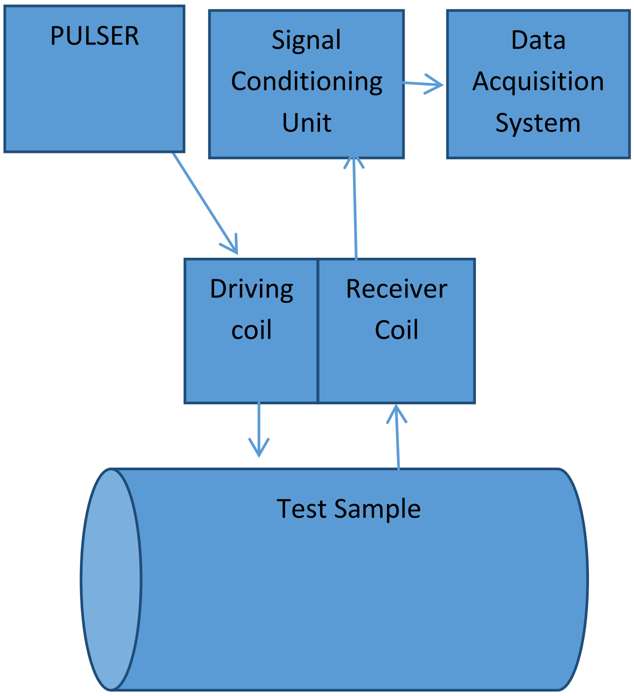

Fig. (5) - Block Diagram of Experimental Set-up

The above block diagram shows the experimental setup. It consists of a Pulser module which was being used to excite the Excitation coil. The flowing current in the Excitation coil will produce its own magnetic field that will penetrate the material. The magnetic field will induce eddy current on the surface of the specimen. The magnetic field of the eddy current will be modulated by the thickness of the Feeder pipelines. The net magnetic field due to the excitation current's field and eddy current's field will be sensed in the receiver coil which being the pickup sensor which will induce emf proportional to the rate of change of magnetic field. The differential signal (as center tapping was done in Receiver coil with center being grounded to eliminate noise pickup)was passed through a high gain Instrumentation Amplifier (In – Amp), which was then passed through the data acquisition module which in this case is a CPCI based Interface. The samples of the received signal were logged there and could be analyzed using PC software both in time as well as in frequency domain. The Signal Conditioning Unit (SCU) consists of an INA – 114 based Instrumentation amplifier circuit having a high CMRR of 115 dB and a high Differential gain of 10 to process the received PEC signal which is finally given to the Data Acquisition System (DAS). Moreover a LM-311N and IC-7805 regulator based down conversion circuit was there to convert the 15 V trigger pulse to 5 V TTL compatible output to trigger DAS from the Pulser.

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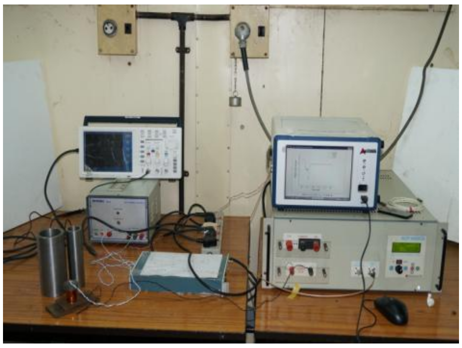
IV. EXPERIMENTAL VALIDATION

The experimental validation started with assembling the integrated sensor containing the Ferrite coil, the Receiver coil and around which the Excitation coil was mounted. Then the continuity of the coils were checked. The next step included measuring the Resistance and Inductance of the Excitation and Receiver coil with a multimeter and a LCQ meter respectively. Depending on the resistance and inductance value of the respective coils the Quality factor of both the coils were found out by using a test frequency of 4 KHz. The properties of Excitation and Receiver coil as found out physically are as follows:-

Table (II) Electrical properties of Excitation & Receiver Coil

Property	**Excitation**	**Receiver**
Resistance(Ω)	165	7
Inductance(mH)	257	2.5
Quality Factor(Q)	39.12	9

Fig. (6) – Experimental Set-up



A .Time Domain Analysis

The Pulser was connected to the Excitation coil and was excited with the waveform having the following attributes:

Voltage – 450 V **Current** – 10 A **On Time** – 10 ms

Pulse Repetition Frequency – 1 Hz

Carbon Steel (ASTM A-333 Gr.6) pipe of 65 NB size with wall thickness of 5.5 mm ,6.5 mm and 7 mm and 32 NB Pipe with wall thickness of 5 mm , 5.5 mm and 6 mm were fabricated as test specimen. The received signal samples were stored in the DAS and its Logarithmic value was plotted against time to correlate with wall thickness. Fig. 7 below shows the Decay curve and Decay coefficient for 65 NB Feeder Pipes.

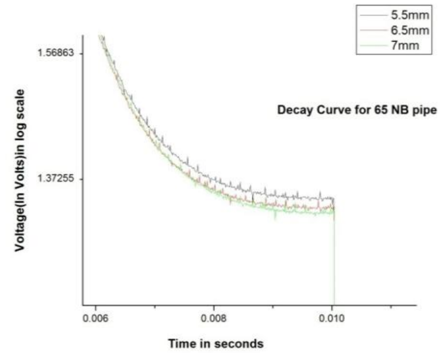


Fig. (7) - The Decay Curves Obtained Experimentally For 65 NB CS Pipe

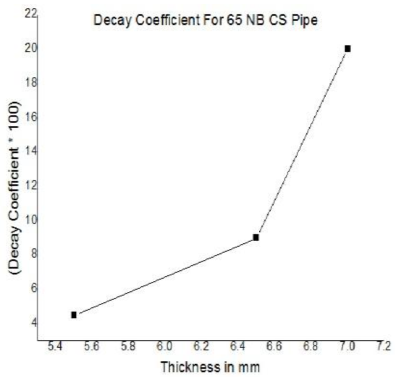


Fig. (8)- The Decay Coefficient for 65 NB CS Pipe with Various Thicknesses

It was seen that the Decay coefficients followed the same trend as found out from the Simulation results, i.e they tend to increase with increase in wall thickness. Fig. 9& Fig. 10 gives the Decay curves and the variaton of Decay coefficient for 32 NB Feeders.

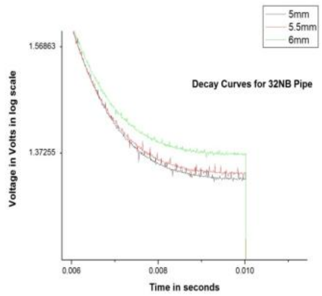


Fig. (9) - The Decay Curves obtained experimentally for 32 NB CS Pipes

The effect of Lift – Off was studied by varying the gap between the sensor and test specimen by 0.1mm up to 0.5 mm and the chracteristics were found to be similar. Hence if the Lift- Off is varied within 0.5 mm then there is no effect on the received waveform. Fig. 11 gives the effect of Lift-Off for CS Pipes.

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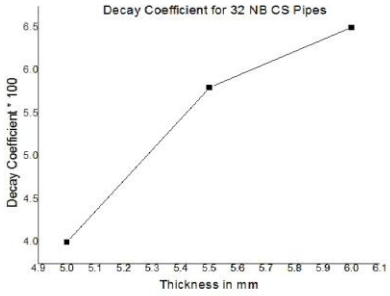

Fig. (10) - Decay Coefficients for 32 NB CS Pipes with various Thickness

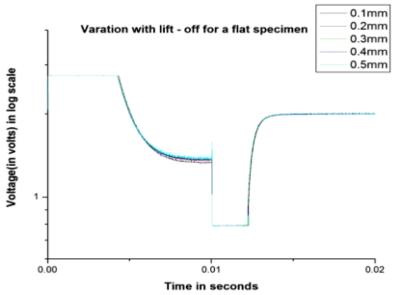

Fig. (11) - Effect of Lift – Off for CS Pipes

B. Need for Time – Frequency Analysis

Non-stationary signals are those signals whose frequency components vary constantly with time. A good example of such a signal may be

x(t) = cos(200*π*t) , for 0≤t≤5

= cos(40*π*t) , 5≤t≤10

= cos(20*π*t) , t>10

For such signals analyzing the signals in frequency domain by using tools like simple Fourier transform will only be able to give information about the frequency components present in the signals but will not be able to furnish information about, at what time those frequency components were present. If we use Fourier transform on another signal like :

x(t) = cos(40*π*t) , for 0≤t≤5

= cos(200*π*t) , 5≤t≤10

= cos(20*π*t) , t>10

Then it will give the same output as the first signal as because it is not able to sense the time at which specific frequency components were present. To, be able to overcome such difficulty Time- Frequency tools are used to analyze such non-stationary signals. Certain methods like Short- Time Fourier Transform, Wavelet Transform and Weigner-Ville distribution are extensively used[14]. Moreover the Spectrogram which is the modulus of the square of such distribution is also used for analysis. For the Analysis of Pulsed eddy Current signal , which being non-stationary consisting of large number of frequency components, Weigner-Ville Distribution was used for it's high temporal and spatial resolution.

C. Weigner-Ville Distribution

This distribution was first introduced by E. Wigner in the context of quantum mechanics (Wigner, 1932), and later independently developed by J. Ville who applied the same transformation to signal processing and spectral analysis (Ville, 1948). In such a distribution a signal S(t) which has to be analyzed is at first processed to find out it's analytical associate (x(t)) which is given as:-

x(t) = S(t) + iH[S(t)]

Where H[S(t)] is the Hilbert transform of the signal S(t). Hilbert Transform is sometimes referred to as a "Quadrature filter" and the transformed signal as the "Quadrature signal," for reasons relating to the phase shifts introduced by the transform. In fact running the transform four times will return the signal to the original signal, as each transformation shifts real frequencies by π/2 and negative frequencies by -π/2. Then the analytical associate is advanced by a factor τ/2 and is correlated with an delayed version by a factor τ/2 of it's complex conjugate [15]. Then the transform of this signal is found out. It is mathematically represented as:-

$W_x(t,\omega)\ \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x\left(t+\frac{\tau}{2}\right)x*\left(t-\frac{\tau}{2}\right)\ e^{-j\omega t}d\tau$, for a continuous time signal

For , a discrete–time signal the corresponding Weigner-Ville distribution function becomes

$$W_x(n,\omega) = 2\sum \sum_{-\infty}^{+\infty} x(n+m)x*(n-m)e - j4\pi fm$$

D. Time- Frequency Analysis of the PEC signal

The PEC signal was sampled at a sampling rate of 10,000 samples per second. Moreover only 4096 data points were collected for analysis. Analysis was done for Curved specimen (both for 65 NB and 32 NB). The frequency sensitive zone in the graph and the specific coordinate which was sensitive to the thickness information was also found out for individual cases. The effect of Lift-off on the index values of coordinates chosen for segregation was also found out. The data samples for a specific specimen were stored in Data Acquisition System (DAS) and a program was written to implement Weigner-Ville distribution on the samples using a Mathematical software[16].

E. For 65 NB Pipe

The data points obtained from the PEC signal were truncated and only 4096 data points out of 5000 data points were given as inputs to the program used to implement Weigner-Ville plot. The results of the Time, Frequency and Amplitude given by the index value are

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given below. The third dimension i.e the amplitude of a particular frequency component is given by a colour whose relative magnitudes are mentioned in the scale given below the figures. From the above plot, the specific coordinate sensitive to the thickness information and least sensitive to lift-off was found out which was observed to be [1268,5.002] . It was found out that the entire spectrum was shifting to the right in the Time-Frequency plane with increase in thickness. The Amplitude also called the Index values at [1268,5.002] was plotted as a function of thickness to correlate between thickness and the corresponding Index variation of a frequency component at a particular time instant. Each division in Y-axis in the graph above corresponds to E-5 seconds as the sampling rate is 10,0000samples/second. Each division in Y-axis corresponds to 50000/2048 = 24.41 Hz. The Time – Frequency spectrum for thickness of 5.5 mm, 6.5 mm and 7.0 mm are given below

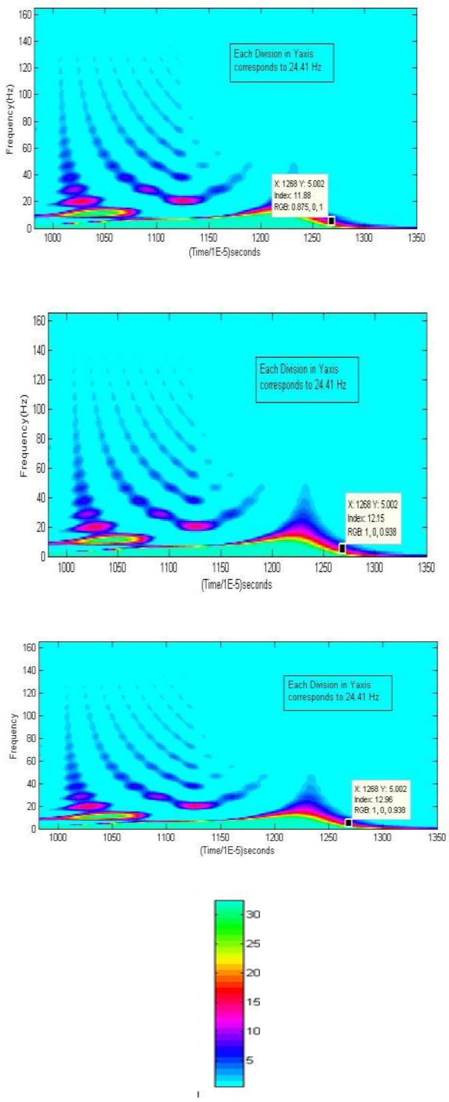

Fig. (12) - The Time - Frequency Spectrum for 65 NB Pipes of Thickness 5.5 mm , 6.5 mm and 7.0 mm respectively along with the colour bar showing the Relative Amplitudes of the Spectral Components

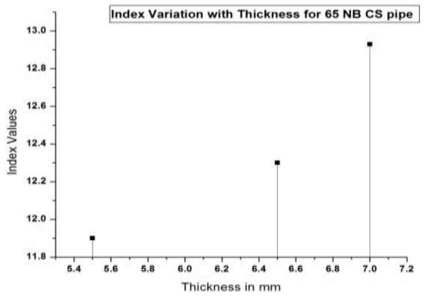

Fig. (13) - Index Variation with Thickness for 65 NB CS Pipe

F. For 32 NB Pipe

The same observation was made for Spectrum of 32 NB pipe which was seen to get shifted to the right with increase in thickness. The variation of Index values with increase in thickness of the specimen is given below:

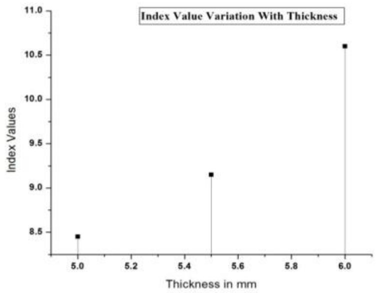

Fig. (14) - Index Variation with Thickness for 32 NB CS Pipe

G. Effect of Lift – Off

Lift-off was varied for 65 NB Carbon Steel pipe from 0.1-0.4mm with increments of 0.1mm and the index values at co-ordinate [1268,5.002] was seen for 6.5mm thick 65 NB CS pipe. It was found that the index values varied within a short range from 12.225 to 12.430 which was not much with respect to the change in index values for step change in thickness. Hence if calibrated properly the minor variation in index values with lift-off can be eliminated easily during field measurements.

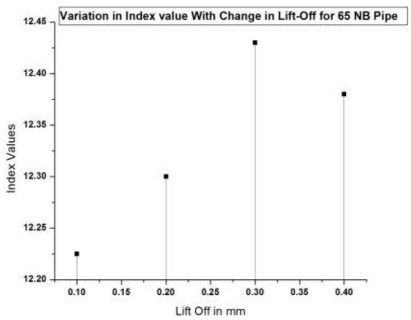

Fig. (15) - Index Variation with Lift-Off for 65 NB CS Pipe

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V. RESULTS AND DISCUSSIONS

The Finite Element Method Simulation Software was used to optimize the sensor size, geometry and also to simulate the response of the sensor for various conditions. At first a 2-D Axis Symmetric model was developed to optimize the sensor geometry and other attributes. Then a 3-D model was designed with the optimized dimensions as formulated using the 2D-Axis –Symmetric model. The optimized dimensions obtained were 20 mm Outer Diameter (OD) for the Excitation coil with an Inner Diameter (ID) if 10 mm and a height of 30 mm. The Receiver coil had the OD of 10 mm & ID of 4 mm with height of 10 mm. A MnZn Ferrite core with operating frequency in the range of 2- 1000 KHz and having high permeability was used to increase the strength of magnetic field. The results obtained were sufficient in differentiating between the thickness of 5.5 mm,6.5 mm & 7.0 mm but decay coefficients were very less with 5 A peak current excitation. So the excitation current magnitude was changed to 10 A and simulation was performed. Better results were obtained in this case and the Decay coefficients obtained for 5.5 mm, 6.5mm and 7.0mmthickness of 65 NB CS pipe were 1.08, 1.75 and 2.9 respectively. The Experimental results obtained with both 65 NB and 32 NB Feeder pipelines were sufficient in differentiating between the corresponding thickness of specimens. The values of the Decay Coefficient for the 65 NB pipe for thickness of 5.5 mm, 6.5 mm and 7.0 mm found experimentally were 3.73, 9.09 and 20. Whereas that with 32 NB pipe with wall thickness of 5.0 mm, 5.5 mm and 6.0 mm were 4, 5.85 and 6.5 respectively. It was also observed during experiments that for a CS pipe 10 Amp peak Pulse excitation is required to properly differentiate between the step changes in thickness as predicted by the simulation results. Then again the effect of Lift off was studied for CS pipe (both 65 NB and 32 NB) and there were not much variation in the results. But it was only observed that in case of Simulation with lift-off variation up to 0.5mm there was no effect on the Decay characteristics, whereas this maximum lift-off value in case of Experimentation was upto 0.4mm beyond which much variation was observed in Time-Frequency analysis. The, Non stationary PEC waveforms found experimentally were analyzed in Time-Frequency plane using the Weigner- Ville Transform and a particular co-ordinate [1268,5.002] was found out whose index value was sensitive to the thickness attribute of the specimens and in-sensitive to the Lift-off variation. This gave a direct correlation between index value and thickness of specimen. It was observed that with increase in thickness of the specimens the spectrum was shifting towards right and the Index value at the selected Time Frequency pair or the selected coordinate was increasing which could be directly correlated with thickness. For 65 NB pipeline the Index values at coordinate [1268,5.002] for 5.5 mm, 6.5 mm & 7.0 mm thickness of Pipes were 11.9, 12.3 & 12.9 respectively whereas the Index values for 32 NB pipeline at coordinate [1268,5.002]for thickness of 5.0 mm, 5.5 mm & 6.0 mm of pipes were 8.5, 9.25& 10.65 respectively which increases with increase in thickness.

VI. CONCLUSION

The designed Pulsed Eddy Current based Feeder Pipeline Wall thickness monitoring sensor can be successfully used with proper calibration for measuring the wall thickness of Feeder Pipelines used in Primary Heat Transport (PHT) system of Indian PHWR's. The sensor developed had a height of 38 mm and a diameter of 37 mm which is well within the limits to be used in Feeder inspections, as the allowable gap between two corresponding Feeders is around 50 mm. The resolution of the sensor was found out to be 0.3 mm as validated experimentally and also according to the simulation results 0.3mm thickness difference between two CS specimens can also be detected by such a sensor. Hence, as the thinning rate of CS Feeder is found out to be around 150 microns/year so, during biannual shutdown of the reactor using such probe Wall thickness measurement can be done as a part of In-Service Inspection. Both Time domain analysis as well as Time- Frequency analysis of the PEC waveform was successful in indicating the thickness information present in the waveform. In case of time domain analysis the logarithm of the slope of the Decaying waveform was used to differentiate between the changes in thickness whereas in case of Time- Frequency analysis the Index value at a particular coordinate (time, frequency pair) which was sensitive to thickness information and least sensitive to lift-off variation was found out and correlated with thickness. Hence, either of these analysis technique can be used to monitor the wall thinning phenomenon in Feeder Pipelines or both the techniques can be adopted for better interpretation of the phenomenon during ISI.

VII. FUTURE ENHANCEMENT

In future the Sensor can be totally Automated and coupled with the DAS to ensure less consumption of Man-Rem to the inspecting personnel during In-Service Inspection (ISI) of operating PHWRs.

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AUTHORS PROFILE

Shri Suvadip Roy is an Electronics Engineer from 56th Batch of BARC Training School. He has done his Post Graduation in Electronics & Instrumentation Engineering. Currently he is working as a nuclear Regulator in Atomic Energy Regulatory Board and is associated with review of Instrumentation & Control Aspects of Nuclear Power Plants. His Area of Interest includes Digital Electronic Systems, Digital Signal Processing, Neutronic Instrumentation, Modern Control Theory & Use of Programmable Logic Devices (FPGA & CPLD) in Safety Critical Applications in Nuclear Power Plants.