ALGORITHM DEVELOPMENT AND CASE STUDY FOR A 1-11/16” PULSED EDDY CURRENT CASING INSPECTION TOOL

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ABSTRACT

Well integrity monitoring is growing in importance as fields’ mature, as oil and gas is exploited in evermore hostile and corrosive environments and due to stricter regulatory requirements. Over the lifetime of a typical well monitoring the completion integrity includes running logs such as cement bond evaluation, production flow logs and tubular inspection. Casing and tubing integrity monitoring often consist of a combination of mechanical multi-finger caliper logs, Electro-Magnetic (EM) pipe thickness logs, Ultrasonic casing inspection logs and down-hole video. These direct inspection logs can be used to monitor corrosion early and help mitigate serious leaks or well failures. When combined with other logs that can indicate abnormal flow conditions such as temperature logs, spinner profiling and passive noise detection logs can assist diagnosis of completion problem that would need intervention.

Electro-Magnetics measure properties sensitive to pipe thickness, with wall thinning associated with corrosion and other pipe defects. Various EM methods have been reported over the years often initially for pipeline inspection and then adapted for down-hole monitoring. These methods include Magnetic Flux Leakage (MFL) and Eddy Current (EC) measurements. Early EM methods were single frequency but later developments include multi-frequency. In this paper we report a technique called Pulsed Eddy Current (PEC) which is inherently multi-frequency and in time domain is radially sensitive, which enables inspection of multiple tubular thicknesses. Most inspection techniques including some EM methods are only capable of inspecting the innermost tubular or only the total thickness of multiple tubulars however a PEC tool can measure separate thicknesses of both inner and a second tubular. This allows quantitative corrosion evaluation of casing without removing the completion tubing.

The paper covers a theoretical review of the PEC technique and development of a forward analytical model tied to experimental data acquired with an actual logging instrument. The forward model is used to ensure optimum tool design and allow development of suitable algorithms to process field data. This is followed by a field case study which demonstrates how this PEC based slim tubing-casing inspection tool can be utilized in combination with other techniques such as multi-finger calipers. We conclude with some pointers to further development of the hardware and data processing techniques.

INTRODUCTION

The physical fundamental of the PEC EM tool is Faraday’s law of induction. When supplying pulsed current into the transmitting coil (or, call it excitation coil) of the tool, there will be time-varying induced electromotive force (EMF) in its receiving coil (or pickup coil). If there is thickness variation, faults or flaws in the pipe string, the induced EMF shall vary from its expected level in time domain. After data processing, one can diagnose defects such as holes, pitting and cracks in the pipe string and measure the pipe string thickness variation.

The applications of PEC EM tool are: 1) measuring the thickness of tubing and casing; 2) detection of corrosion and damage of pipe strings; and 3) detection of the horizontal and vertical crack, fracture and deformation of pipe string.

In one version of a PEC EM tool there are four separate sensors as follows:

- The A sensor is the main sensor of the tool as shown in Fig. 1. This sensor has the deepest depth of investigation and is sensitive to corrosion and defects on an inner and outer tubular (often the completion tubing and the production casing). This axially mounted sensor is sensitive to vertically oriented thickness variation;

- The B and BB sensors are mounted perpendicular to the tool axis and are more sensitive to horizontal defects within the innermost tubular string;

- The C sensor is a shorter axial sensor as shown in Fig. 2. It is sensitive to smaller vertical defects within the innermost pipe string.

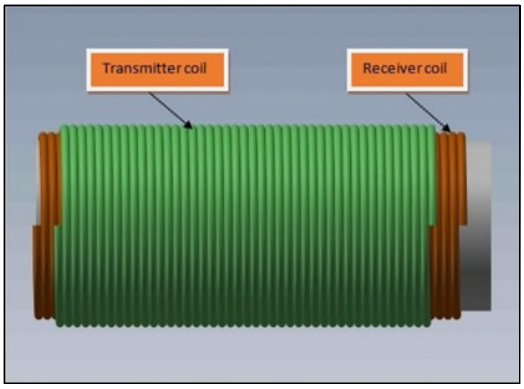


Fig.1 “A” Sensor – co-located excitation (Transmitter) and pickup (receiver) coils

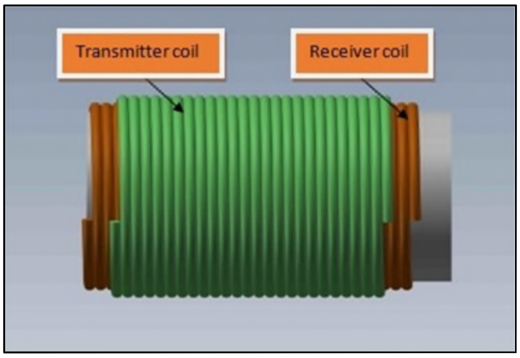
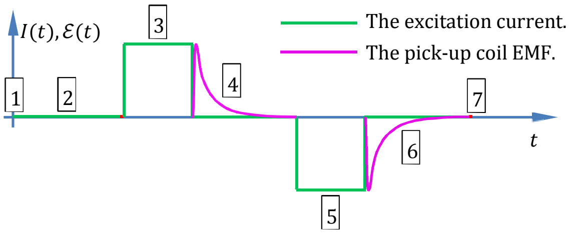


Fig.2 “C” Sensor – co-located excitation (Transmitter) and pickup (receiver) coils

The magnitude of the time-varying current in the excitation coil and that of the measured EMF in the pick-up coil are shown in the figure 3.



1. Initialization
2. B & BB sensor acquisition
3. A and C sensor positive Excitation
4. A and C sensor data acquisition
5. A and C sensor negative Excitation
6. A and C sensor data acquisition.
7. Averaging data from step 4 and 6 and output.

Fig.3 The time sequencing of the sensors.

The excitation current increases quickly to a peak value and then suddenly drops to zero. This pulse of excitation current causes a sudden change in the magnetic field that generates an inductive electrical field.

Conductors (such as tubulars) within this electrical field respond with a time-varying eddy current as shown in Fig. 4. This eddy current generates a secondary magnetic field that changes with time. This varying secondary magnetic field results in a change of magnetic flux at the pick-up coil.

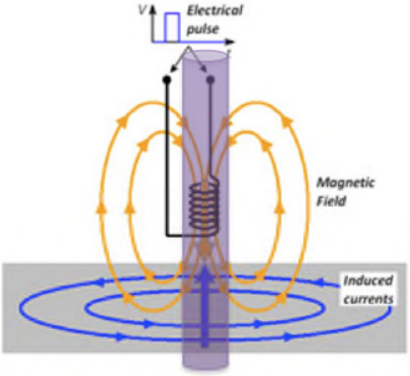
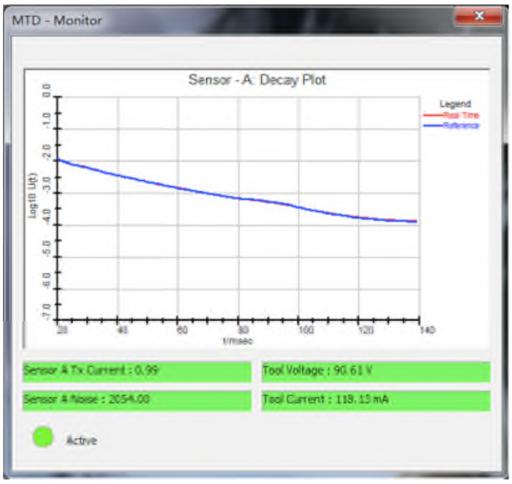


Fig.4 Illustration of the magnetic field and induced eddy current surrounding the excitation coil in the tool.

After a brief while the effects of the primary field dissipate while the eddy currents within the conductors still exist. The magnetic field generated by the varying eddy currents generates the EMF within the co-located pick-up coil. The measured EMF is then processed to increase the Signal-to-Noise Ratio (SNR). In Fig. 5 there is an example of the time varying decay signal from sensor A that is used for quality control (QC) of the tool response during log acquisition. The vertical axis is the voltage at the pickup coil scaled logarithmically. Abnormal non-monotonic behavior and excessive noise can be easily identified while logging and the necessary corrective action taken.



Sensor A Tx Current : 0.99

Tool Voltage : 90.61 V

Sensor A Noise : 2054.00

Tool Current : 118.13 mA

Fig.5 Real time QC display

ANALYTICAL FORWARD MODEL

An analytical model of the PEC EM tool has been developed to predict the tool's behavior quantitatively. This model allows sensitivity analysis to understand the tool response behavior and is used to develop the algorithms to calculation pipe thickness and defect evaluation.

In evaluating the EM effects of the tool, the vector potential $\underline{A}(\underline{x};t)$ is applied. This vector potential satisfies the following differential equation of diffusion form (1), which is derived from Maxwell's equations:

$$\nabla^2 \underline{A}(\underline{x};t) - \mu\sigma \frac{\partial \underline{A}(\underline{x};t)}{\partial t} = -\mu \underline{J}_s(\underline{x};t)\,. \qquad (1)$$

Here σ and μ are electrical conductivity and magnetic permeability respectively of a medium considered, and $\underline{J}_s(\underline{x}\,;t)$ is the density of excitation current.

For the simplified case of linear, isotropic and piece-wise homogeneous media, the pipe strings along with the tool itself are seen as a series of tubular structures with axial symmetry. Thus the tool response in terms of EMF $\mathcal{E}(t)$ in its pickup coil to the input current $I(t)$ could be derived from equation (1) as:

$$\mathcal{E}(t) = C \int_{-\infty}^{\infty} I(\omega) Z\left(\omega, \underline{r}, \underline{\sigma}, \underline{\mu}\right) \mathrm{e}^{\mathrm{i}\omega t} \mathrm{d}\omega\,, \qquad (2)$$

where $I(\omega)$ is the input electrical current in frequency domain, C is the constant of the tool configuration, and $Z\left(\omega, \underline{r}, \underline{\sigma}, \underline{\mu}\right)$ can be considered the system's transfer function. This function is dependent on the circular frequency of EM wave ω, the radii of all interfaces in the tubular structures, $\underline{r}$, and the EM parameters of all media layers, $\underline{\sigma}$ and $\underline{\mu}$. Given the radii $\underline{r}$ of all tubular layers, the thickness of any pipe string can be calculated from the difference of its inner and outer radii.

This computed EMF $\mathcal{E}(t)$ is equal to the voltage at the pick-up coil, which is then further processed by a series of filters simulating the effects of the measurement instrumentation. This includes increasing downhole gain to boost the late time signal that can drop by 30db. Finally the gain adjusted EMF signal is converted into time sliced channels representing a series of time periods over the measurement window. These channels are denoted A_1 to A_{11} for sensor A, and similar for the other sensors.

To validate the newly developed forward model, a series of experimental data was acquired with the tool in different pipe sizes and combinations. These experiments confirmed the model was accurately predicting the tool behavior in a wide range of pipe strings combinations. The virtual simulations by using COMSOL software have also been implemented to cross-verify the analytical model. COMSOL is FEM-based commercial software. Figs 6 and 7 show two typical comparisons among three methods. In these examples the non-monotonic behavior is normal as these responses include the variable downhole gain and unequal width time-channels. There is a close match between the forward model results and real tool outputs made during the experiments. Experiments and modeling were performed using typical oilfield tubing and casing with sizes ranging from 2-7/8" up to 10-3/4" in both single and dual pipe configurations. Once the forward model has been benchmarked against real tool data (we used over 15 different pipe string configurations) the model including analytical and COMSOL models can be used to predict behavior without time-consuming experiments.

SENSITIVITY ANALYSIS

Systematically varying model inputs and inspecting the corresponding outputs allows the researcher to gain insight into the system response behavior. The most important sensitivity to understand is how tool responses to changes in pipe thickness. Firstly the model is used to predict the behavior in a two-pipe configuration with an inner 2-7/8" (6.5#) tubing and outer 7” casing (23#) both with nominal thickness values. The modeled tool outputs designated, A_{N1} toA_{N11}, are used as reference values to normalize every other test case, this makes it easier to observe the effects of the thickness changes. In Fig. 8 the inner 2-7/8” pipe thickness is varied from +10% (i.e. pipe thickening associated with a collar coupling) to -60% (severe corrosion). What is noticeable is a positive increase to pipe thickening on all channels and a near linear decrease with pipe thinning on the various channels. In Fig. 9 the outer 7” pipe thickness is varied from +10% to -60% while the inner tubing is held fixed at nominal thickness. There the early time channels, A1 to A3, do not respond to the outer pipe thickness variations. Hence we are able to separate the effects of thickness variation in the inner pipe (2-7/8” tubing) and outer pipe (7” casing) by analysis of this time domain signal. This is further shown in Fig. 10 where the families of curves are the response variations to simultaneous changes to both inner and outer pipe thickness variations. On further inspection the responses shown in Fig.10 can be considered a superposition of the separate responses shown in Fig.8 and 9. This is a useful finding when considering methods to solve for thickness with an inverse model.

LOG PROCESSING

An easier way to visualize the responses shown in Fig. 8 – 10 is to use a color VDL map where the nominal response for each channel is colored green, positive values (thicker than nominal) are blue and negative values (thinner than nominal) are red. The VDL is then displayed with early-time channels in the left most position and late-time channels in the right most position. Fig. 13 shows a typical example VDL showing inner, outer pipe collars in blue and localized pipe damage in red. In this example channels from multiple sensors are shown in the following order: B1, BB1, B2, BB2, C1, C2, A1, A2, C3, C4, A3, A4, C5, A5 until A11. This sequence best represents the spatial sensitivity in a single display.

While the color VDL provides a user-friendly visual identification of pipe anomalies, such as penetrations, this display is not quantitative as anomalies are enhanced. The next step in log processing involves generating thickness values for the inner and outer tubulars, typically the tubing and casing. As indicated in the Fig. 9 the early time channels are not affected by an outer pipe much and are only sensitive to inner pipe thickness variations approximately. Thus by choosing one or more channels in this early time region an inner pipe thickness can be computed independently of any outer pipes present. The basic processing steps are:

- Select appropriate inner pipe channels based on pipe sizes and their combinations using a look-up table.
- Compute the reference response of the chosen channels for the known nominal pipe thickness. This involves deriving from the log data the pipe properties of electrical conductivity and magnetic permeability
- At each depth sample compute the inner pipe thickness from the variance between the measured tool data and the reference response (as calculated in step 2).

The steps to compute an outer pipe thickness are similar, firstly late time channels are chosen such that pipe collars are clearly detectable. When the inner pipe thickness is computed there is an additional variance factor that is used to correct the late time channels to derive the outer pipe thickness.

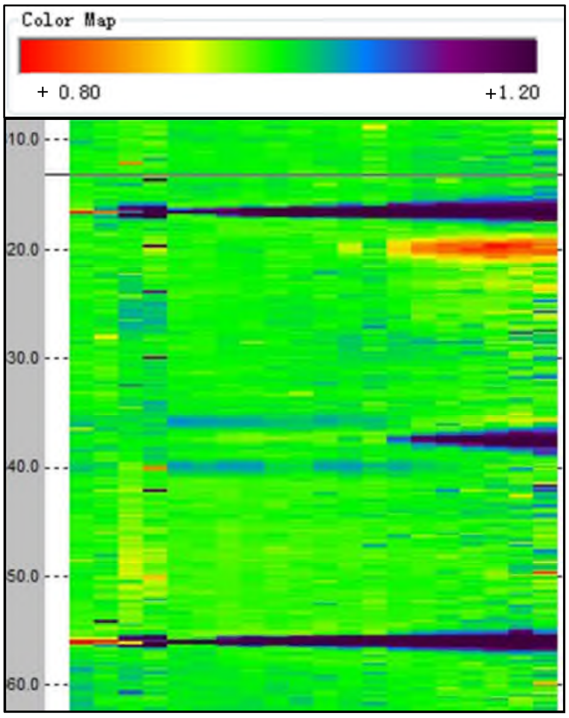


Fig.13 Log display showing two 2-7/8” tubing collars (x17ft and x57ft), a 7” casing collar (x37ft) and pipe damage in the 7inch casing (x20ft)

For comparison purposes Fig.19 shows an interval from a 5-1/2“ casing completion where metal loss calculated from a multi-finger caliper (24 arm) is compared to percent metal loss from EM PEC log. There is a good match between the logs indicating the metal loss is internal.

CASE STUDY EXAMPLE

Over the intervals of interest in this well there is a 4-1/2” tubing completion and a 7” casing string, then shallower there is a third string of 9-5/8” casing. Fig.14 shows a significant tubing penetration at xx61ft just above a tubing collar, also seen is a 7inch casing collar at xx73ft. Fig.15 shows another occurrence of tubing damage.

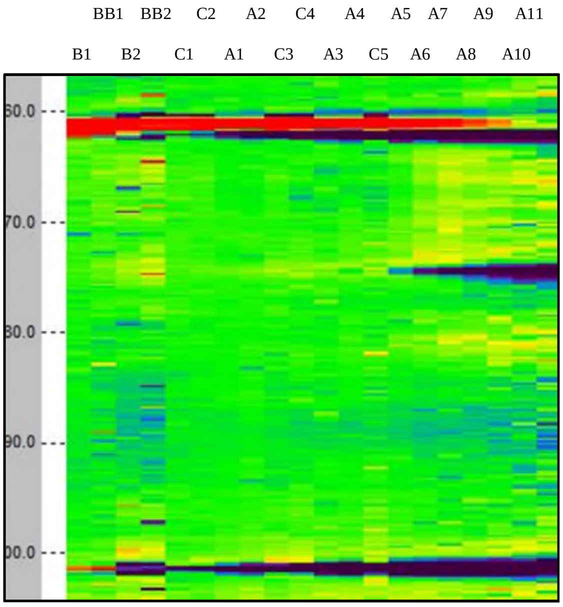


Fig.14 Significant 4-1/2” tubing penetration immediately above the tubing collar at xx61ft. The 7” casing collar is seen at xx73ft. The VDL insert (B1, BB1 etc) is applicable for all the following figures.

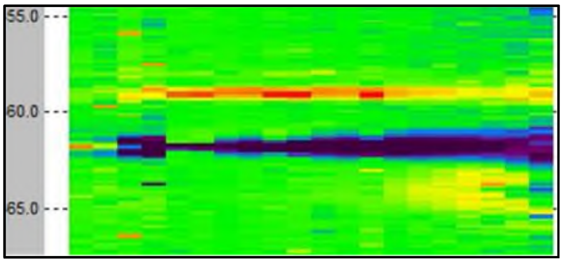


Fig.15 Tubing damage seen at xx59ft around 2ft above a collar

In contract to a multi-finger caliper tool that measures diameters to form a 360 degree image of the internal pipe wall, the EM PEC tool is an omni-directional device that responds as an average around the pipe circumference. The VDL from a PEC EM tool can be considered radially not azimuthal sensitive. The consequence of this averaged measurement is that determining whether significant damage is actually a hole in the pipe (i.e. 100% penetration) relies on a probabilistic approach which is improved when other collaborating evidence exists. Fig. 16 shows a log section where several intervals have 7” casing damage outside the 4-1/2” tubing. Interestingly opposite these intervals the gamma ray log is significantly elevated possibly indicating a penetration with associated scale buildup.

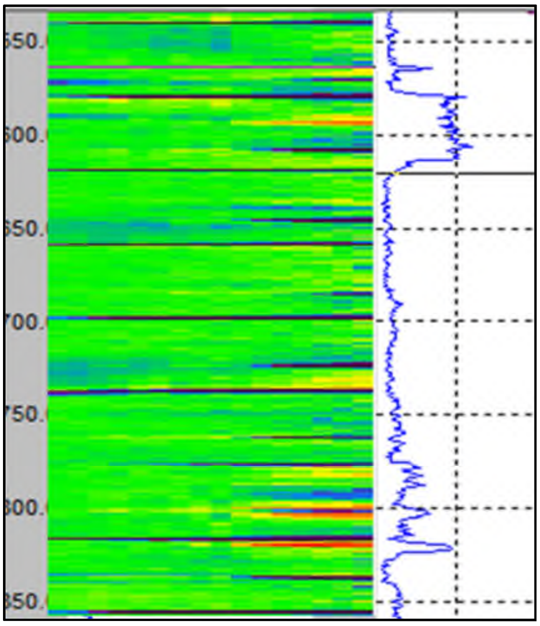


Fig.16 7” casing damage noted at x590ft, x800ft and x820ft with corresponding natural Gamma Ray (blue trace 0-80API) increases, indicating a possible penetration and scale buildup.

At a shallower depth interval in this well above the 9-5/8” casing shoe there are three tubulars that are seen by the EM PEC tool. With the current generation tool evaluation of a 3rd pipe is limited to qualitative identification of intervals of significant damage. The example in Fig. 17 shows a problem in the 9-5/8” casing between xx40-xx42ft where there is also a corresponding increase in gamma ray activity above this depth. By inspection of the signature shown in the VDL display and comparing to nearby collar responses this allows the interpreter to evaluate whether the damage is from a second or third pipe. An example of the log responses from 3 tubulars (4-1/2”, 7” and 9-5/8”) is shown in Fig. 18 where the collars are seen and damage in the 9-5/8” casing is observed.

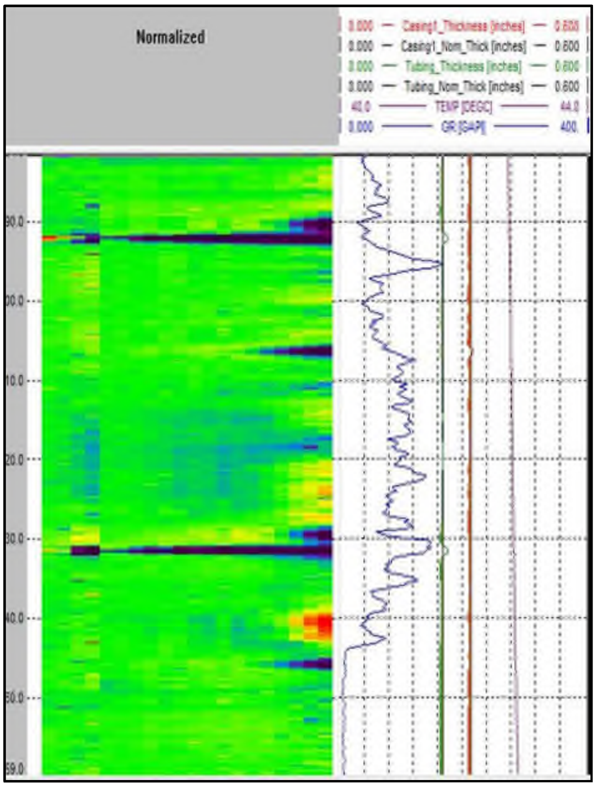


Fig.17 Collars in the third 9-5/8” casing are visible at xx90 and xx30ft. There are Tubing collars seen at xx92ft, xx32ft and 7” casing collars seen at xx06ft and xx46ft. At xx40ft there is damage indicated in the 9-5/8” casing.

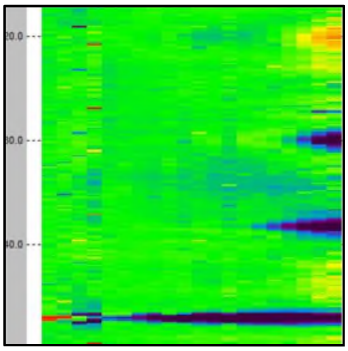


Fig.18 Log response from three tubulars are clearly seen here where the deepest is the tubing collar, followed by the 7” and then 9-5/8” casing collars. At xx20ft is some damage in the 9-5/8” casing.

In many cases combining various log data together can be more diagnostic than a single type of measurement. Fig. 20 shows an interval of pipe deformation on both multi-finger caliper and EM PEC casing inspection logs. The interval of pipe buckling generally shows as metal gain on the casing inspection log and the multi-finger log shows the pipe is oval shaped, the temperature log clearly shows anomaly associated with the damaged pipe. In this case the combined dataset is more diagnostic than any single measurement.

SUMMARY

We have described a through-tubing casing inspection tool based on pulsed eddy current that operates in the time domain that allows evaluation of casing damage from inside a tubing completion. The processing methodology allows damage and metal loss in the first and second barrier to be evaluated quantitatively and with the current tool qualitative evaluation of damage in a third barrier. An EM PEC casing inspection tool is combinable with other measurements including multi-finger caliper tools, gamma-ray and high resolution borehole temperature logs. This combination allows a diagnostic evaluation of well integrity when coupled with a comprehensive interpretation.

Future enhancements to this EM PEC technique include quantitative evaluation of a third pipe by changes to the signal processing in the tool and increasing the pulsed transmitter power. This hardware changes would be coupled with an improved inversion processing algorithm that can solve for three unknown pipe thicknesses.

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Qiuzhao Dong is a Sr. Physicist responsible for EM development with GOWell based in Houston. She is currently focused on EM based casing inspection modeling and simulation work. Before joining GOWell, she worked in LWD/MWD EM-related project for Ryan Directional – A Nabors Company. For 5 years prior to this she worked with Pathfinder – A Schlumberger Company focused on LWD/MWD resistivity tool, EM telemetry and magnetic ranging development. She holds a Ph.D. in Computational Electromagnetism from Northeastern University in USA, MS and BS in Physics from USTC of China. She is a member of SPWLA and SPE societies.

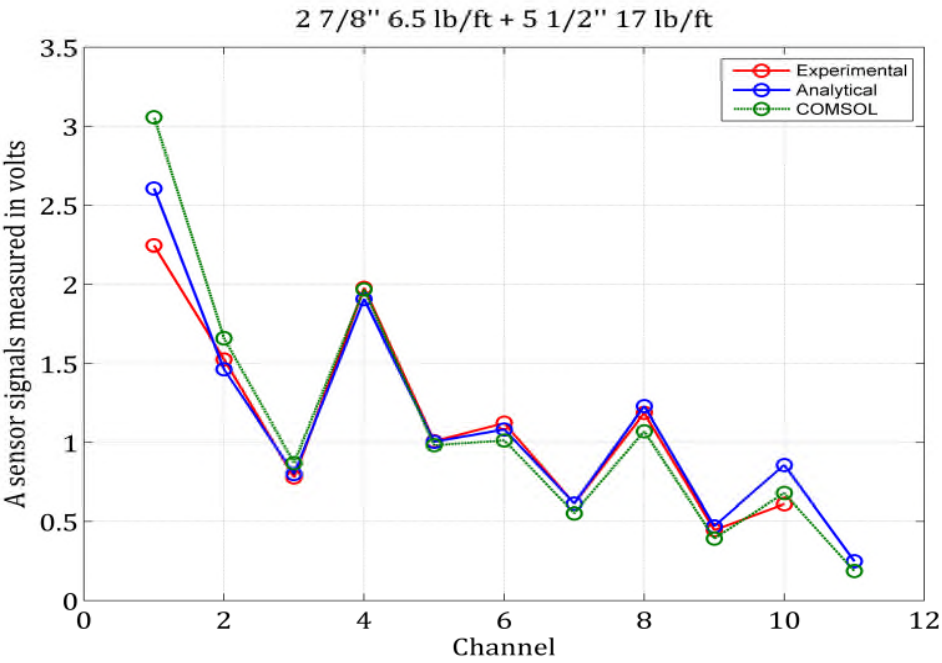

Fig.6 Comparison of results calculated from analytical, COMSOL(FEM) and lab experiments, of two pipe strings combination: inner pipe: $2\frac{7}{8}$" of 6.5 lb/ft , outer pipe: $5\frac{1}{2}$" of 17 lb/ft.

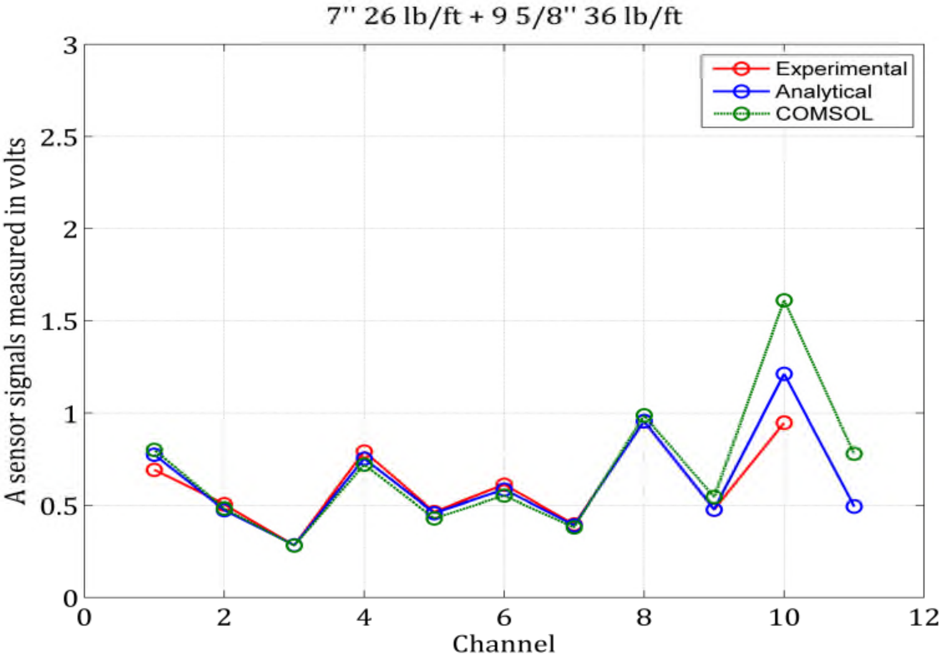

Fig.7 Comparison of results calculated from analytical, COMSOL(FEM) and lab experiments, of two pipe strings combination: inner pipe: 7" of 26 lb/ft, outer pipe: $9\frac{5}{8}$" of 36 lb/ft.

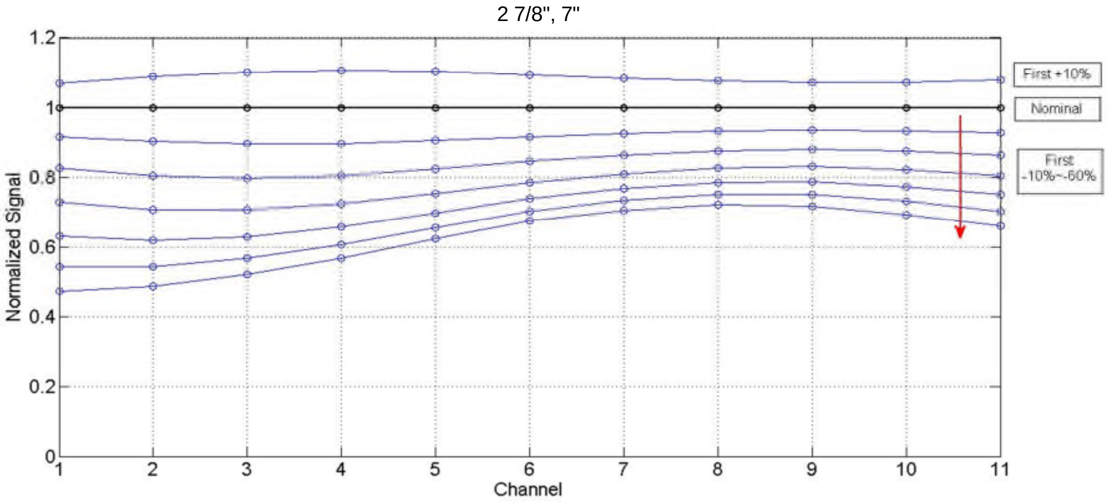

Fig.8 Sensitivity analysis - Inner pipe thickness variations in a two-pipe configuration (2-7/8” and 7”)

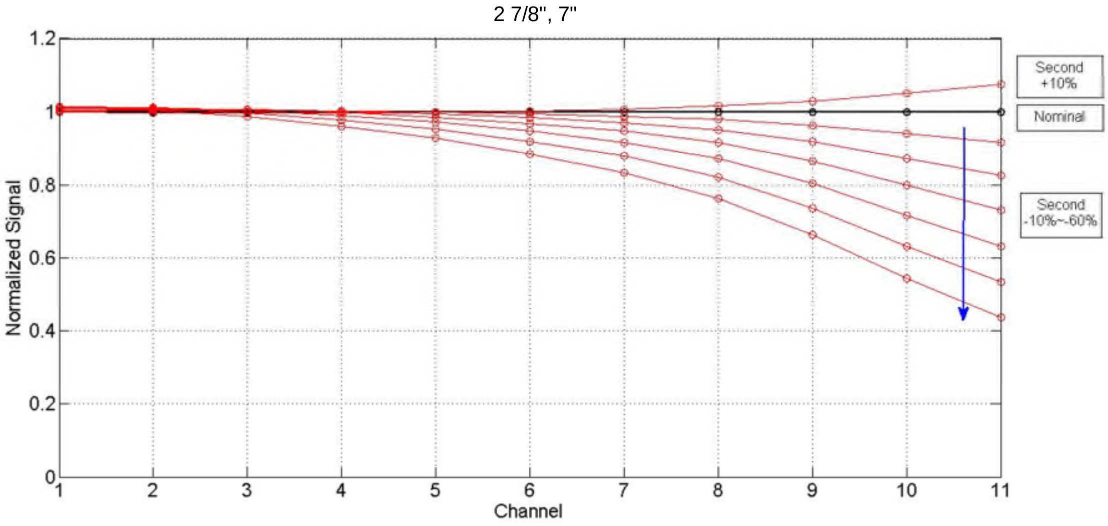

Fig.9 Sensitivity analysis - Outer pipe thickness variations in a two-pipe configuration (2-7/8” and 7”)

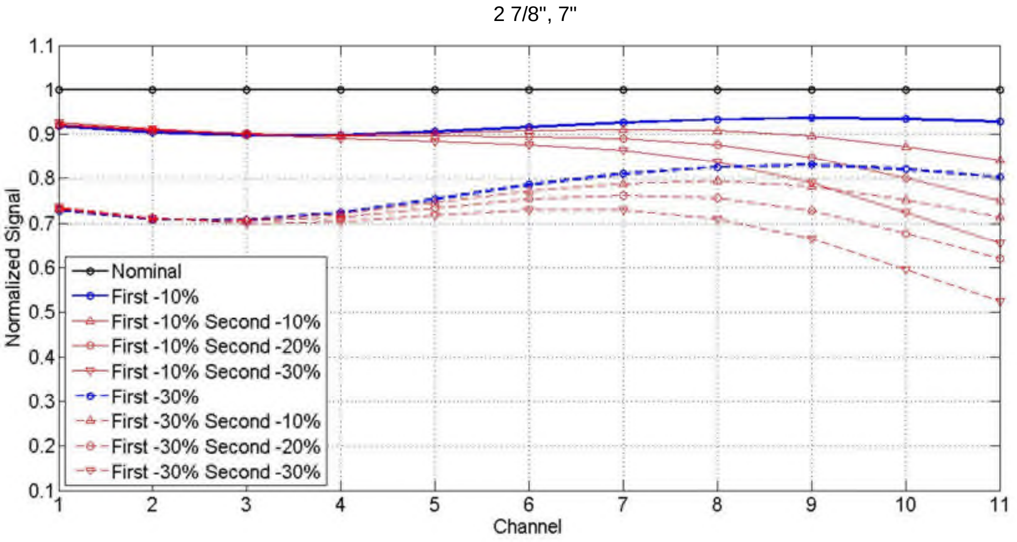

Fig.10 Sensitivity analysis – Combined Inner and Outer pipe thickness variations in a two pipe configuration (2-7/8" and 7")

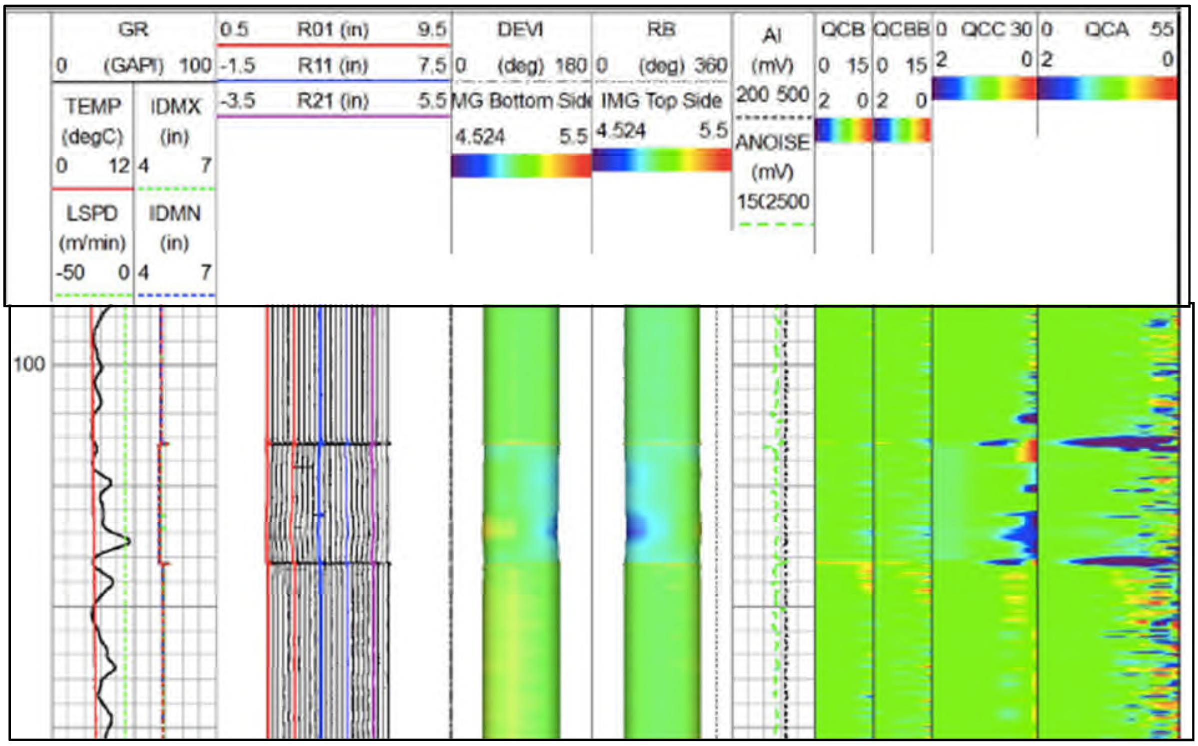

Fig.11 Real Time Log generated during acquisition showing a Multi-finger caliper and EM PEC VDL log.

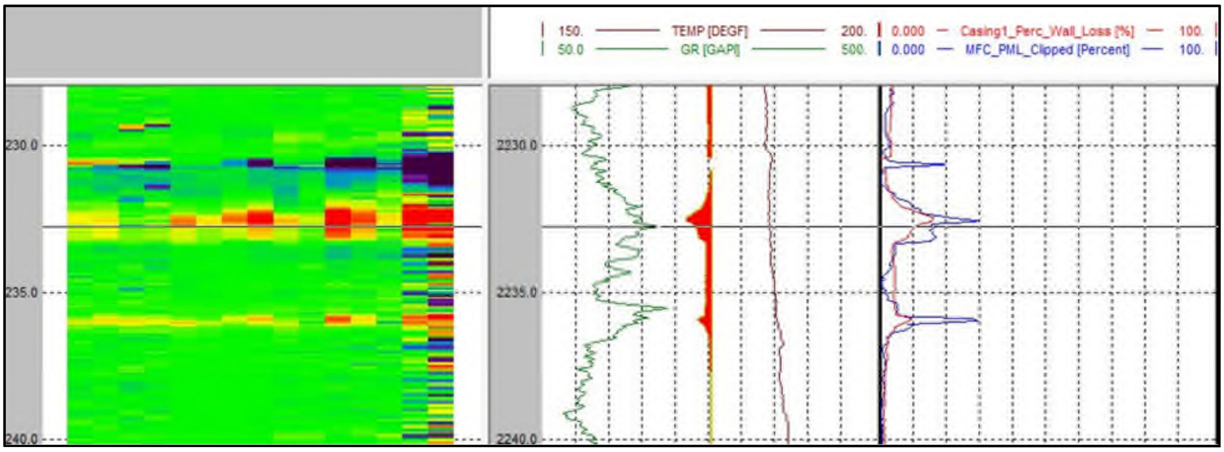

Fig.19 A comparison between multi-finger caliper and EM Thickness Log over an interval showing a pipe collar at 2232m and pipe damage at 2232.5m and 2236m. Track 3 shows Wall Loss % (Perc_Wall_Loss) from the EM PEC tool and Metal Loss % (PML) from a multi-finger caliper log (24 arm). There is a good match between the two calculated metal loss with any slight variation due to the difference in vertical resolution.

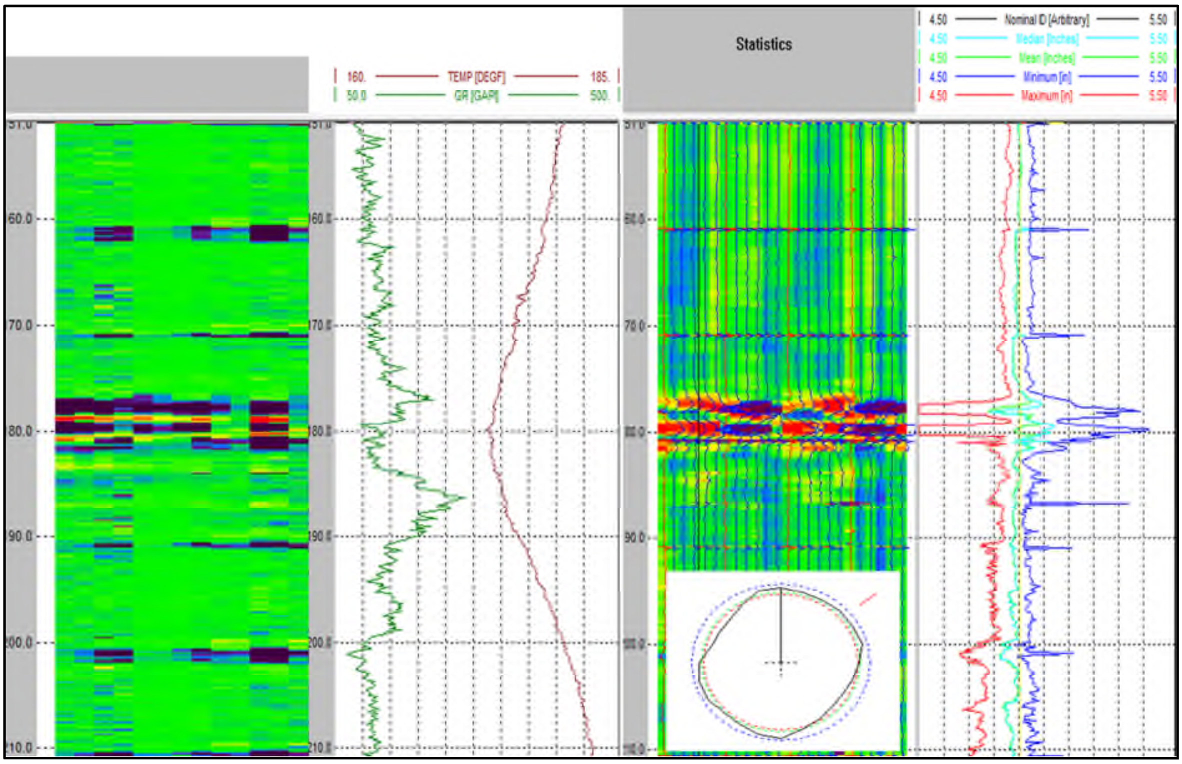

Fig.20 Composite log of EM PEC casing inspection (left two tracks) and multi-finger caliper data (right two tracks) showing an interval of pipe deformation which is characterized by the 2 cycles of red and blue seen on the caliper log (casing has become oval shaped). Here the EC PEC log is generally showing an increase in pipe thickness due to the pipe buckling. The temperature log clearly shows anomaly at this depth interval indicating severe pipe damage and penetration.