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INFORMATION CONTENT IN PULSED EDDY CURRENT MEASUREMENTS FOR EVALUATION OF FOUR AND MORE METALLIC BARRIERS IN OIL AND GAS WELLS

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ABSTRACT

Metal casing corrosion evaluation using electromagnetic (EM) measurements supports environmentally friendly and efficient hydrocarbon production and regulation-compliant well abandonment at the end of the productive well life. The innermost production tubing can be located inside up to six nested metallic casings. In addition to the uncertainty in casing properties, reduced sensitivity and vertical resolution to outer casing corrosion, the EM responses are further complicated by casing eccentering and metallic profile heterogeneities [1,2].

The EM multi-barrier evaluation can be based on continuous wave (CW) and pulsed eddy current (PEC) measurements. While advanced processing [2-4] enables quantitative evaluation of multiple nested casings from multi-spacing and multi-frequency CW, PEC methods [5] rely primarily on time-to-depth mapping for interpreting individual casing thicknesses.

In this work, we present a first systematic sensitivity study and information content analysis for evaluation of four or more barriers using PEC sensors of varied lengths. The data resolution concept is used in the study. Three-dimensional finite element modeling is performed for casing eccentering and nearby casing heterogeneities (collars and defects) to demonstrate additional challenges in interpreting outer barriers.

Keywords: pulsed eddy current sensors, multiple-casing corrosion inspection, multibarrier evaluation

1. INTRODUCTION

Casing corrosion analysis is pivotal in well integrity evaluation. Sensitivity to metal loss, makes the low-frequency electromagnetic (EM) corrosion measurements a viable nondestructive diagnostic means [1]. During completion of a well, the innermost metallic barrier is usually the production tubing, followed by up to six nested casings, depending on the geographical location and legal requirement. The space between each set of barriers, called the annulus, is usually cemented for structural strength, which remains transparent for EM corrosion evaluation. Pipe centralization is sometimes attempted only in intervals where good cement placement is desired, yet varying levels of eccentering are normally observed in pipes.

EM multi-barrier corrosion inspection is classified into two categories: continuous wave (CW) and pulsed eddy current (PEC) methods. Advanced processing [2-4] of multi-spacing and multi-frequency CW enables quantitative evaluation of multiple nested casings. The CW sensors rely on remote field eddy currents for total metal loss of up to 3in. metal thickness for maximum pipe outer diameter (OD) of 36 in., whereas the multi-string evaluation is primarily relying on near field sensors, typically using multiple receivers operating at one or more frequencies, combined with inversion-based processing. PEC methods [5] rely primarily on time-to-depth mapping for interpreting individual casing thicknesses for up to three inner casings, although some vendors recently reported ability to resolve the first four casing thicknesses [6]. The PEC sensors typically have collocated antennas, with the length of the sensor determining the depth of investigation and ability to diagnose large size pipes. Typically, a combination of short and long sensors is used to interpret casing thicknesses [5].

2. METHODS

Sensitivity analysis is performed using 3D time-domain finite element solver (TDFEM). The information content in the PEC measurements is assessed using data resolution matrices [7,8]. For better representation of exponentially decaying PEC casing response, the measurement sensitivities are analyzed by using relative difference in measured signal V from the nominal response in centered noncorroded setting, V_{nom}, given as:

$$\Delta v_r = \frac{V_{nom} - V}{V_{nom}} \tag{1}$$

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2.1 Time Domain EM Modeling

A 3D TDFEM solver using implicit Euler time stepping is used to model collocated pulsed eddy sensors with a magnetic core. The accuracy of the solver is benchmarked against the finite-difference-time-domain (FDTD) solver [9]. For simulation of 15 in. long sensor response inside three concentric casings, a 10° slice of geometry leads to 370,000 degrees of freedom (dof), requiring 2 GB memory and 10 min. to complete the simulation on a standard four-core PC. For eccentered casings, at least 180° of geometry must be modeled, leading to 1.9 million dof, requiring 60 GB memory and 10 hours of simulation time. The sensor responses are generated using 0.5 ms time-step.

2.3 Data Resolution Matrix

In practice, it is important to know how well measurements can resolve the chosen model and if there are model parameters or combinations of model parameters that cannot be resolved. The data resolution matrix is a measure of how well the measured data are resolved by the predicted model parameters:

$$\hat{\mathrm{d}}=\mathbf{R^{data}}\cdot \mathrm{d^{obs}} \qquad (8)$$

In the ideal case, $\mathbf{R^{data}}$ is the identity matrix and should be independent of the model [7]. In reality, perfect resolution can never be attained [8]. The diagonal entries $\mathbf{R}^{\mathbf{data}}_{i,i}$ describe the importance of each data point d_i^{obs}. The i^{th} row of $\mathbf{R^{data}}$ shows how the reconstruction data point $\hat{d}_i$ depends on the other data points. The higher the importance, the less is the reconstructed data point dependent on the other data points and the more influence it has on the overall information content of the measurements [7]. For linear problems, the data resolution is defined in terms of generalized inverse **G,** relating data d and model m, **G** m = d as

$$\mathbf{R^{data}}=\mathbf{G}\cdot\mathbf{G^{-g}} \qquad (9)$$

It is a counterpart to the model resolution matrix defined as $\mathbf{G^{-g}}\cdot\mathbf{G}$, where generalized inverse $\mathbf{G^{-g}}$ relates the model and the data, d=$\mathbf{G^{-g}}$ m.

For the nonlinear problems as PEC corrosion evaluation, the data resolution matrix can be approximated in terms of sensitivities (Jacobian matrix, **J**), and is parameter dependent,

$$\mathbf{R^{data}}\approx \mathbf{J}\cdot\mathbf{J}^{\mathrm{T}} \qquad (9)$$

The complete analysis would require at least single-step linearized inverse routine [8]. In this study it is assumed that the true value of parameters is resolved, and Jacobian is computed accordingly.

3. RESULTS AND DISCUSSION

Figure 1 shows the simulated PEC Δv_r sensitivity results for 20 in. long sensor, logged inside four casings with OD's of 4.5 in., 7 in., 9.625 in. and 13.375 in. and nominal thicknesses Δ_{nom} 0.271 in., 0.362 in., 0.395 in. and 0.435 in. The left set of four tracks shows Δv_r sensitivities when there is only 1ft. long 10%, 20%, 30% and 40% azimuthally symmetric loss, respectively, appearing in four casings one at a time. The responses are symmetric with respect to the defect midpoint. It is also evident that the sensitivities are delayed in time for the outer casings, which is the foundation of the conventional time-to-depth transformation for assessing individual casing thicknesses [5]. However, as evident, the later time responses are also affected by change in inner casings which is hard to resolve using a conventional time-to-depth transformation. In addition, large losses in the outer casings lead to increased uncertainty in inner casing thickness, whereas inner casing eccentering reduces the apparent outer casing losses from the time-to-depth transformation [1].

The right set of four tracks shows the corresponding Δv_r sensitivities with a 1ft. long collar, represented as 50% extra metal immediately below the individual defects, centered at -12 in. for each of the casings. For all four cases, the presence of the collar significantly reduces the sensitivity to casing losses.

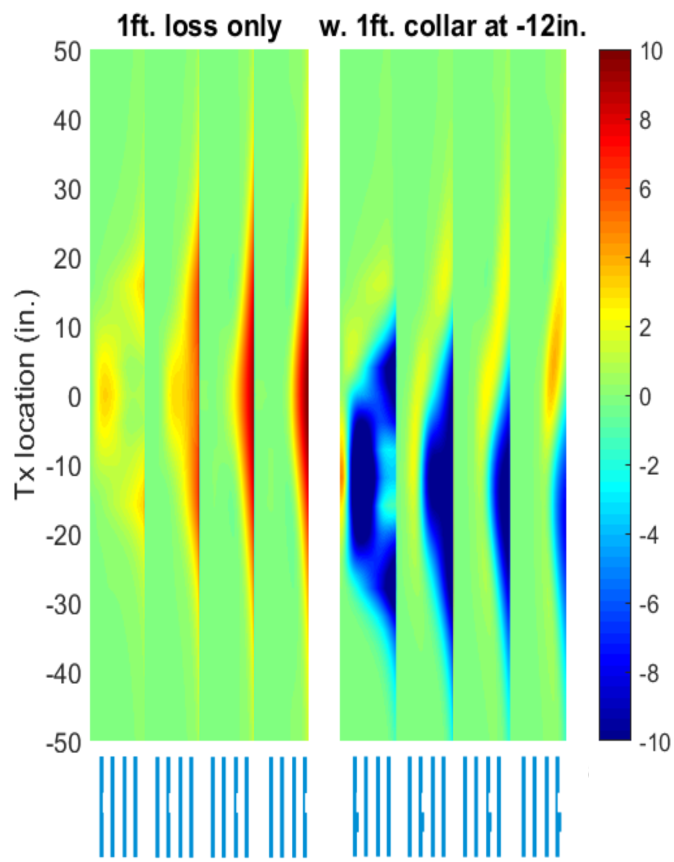

FIGURE 1: 20 in. SENSOR ΔV_R RESPONSE FOR 1 FT. LONG DEFECT (10%, 20%, 30% AND 40% AZIMUTHALLY SYMMETRIC LOSS, RESPECTIVELY) INDIVIDUALLY IN FOUR CASINGS WITHOUT AND WITH 1FT. LONG COLLAR (50% METAL GAIN)

The information content in PEC measurements from sensors of varied length will also be presented in the full paper.

4. CONCLUSION

With an increasing number of casings to be evaluated, the limitations in measurement as well as interpretation techniques and information content in PEC measurements are systematically analyzed to understand the limitations and potential ambiguities and demonstrate the need for 3D modeling and advanced processing techniques in evaluating four or more casings using PEC technology.

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