Off-centering robust calibration of Eddy Current Array Probe used in Power Plants Steam generators

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Abstract

Eddy Current examination of Nuclear Plants steam generator tubes can be done with an inside tube array probe consisting of 32 pancake coils (16 on the circumferential and 2 rows of coils in the axial direction). In EDF standard, each steam generator tube is inspected in line with a calibration tube containing artificial flaws allowing for standardization of probe signals and checking of its functionality. The array probe being an emitter to receiver in absolute mode type of probe, it is sensitive to off-centering, especially with probe ageing. In this paper, we present signal processing algorithms improving calibration with a probe affected by off-centering effects. We start by exploring the cyclic noise related to off-centering on a flawless part of the calibration tube. This leads to assume that the off-centering noise is independent along the tube axis and sinusoidal of period one along the tube circumference. Then, using an additive signal plus structured and white Gaussian noise model, we derive two filters assuming or not that the signal of interest is approximately calibrated. Finally, we explain how to use these filters to derive robust calibration coefficients and reconstruct a noise plus calibrated signal in order to achieve the steam generator tubes inspection.

1. Introduction

The Eddy Current examination of Nuclear Plants steam generator tubes is a very demanding process. Challenges include: high number of tubes (up to 5300 per steam generator), small flaws and complex signal analysis, data to be reviewed quickly with precision and accuracy... According to the nuclear plant, the steam generator tubes diameter can be 7/8” or 3/4”, and the tubes alloy can be Inconel 600TT or 690TT. In this paper, we limit ourselves to the tubes made of Inconel alloy 600TT with outside diameter 19.05mm (3/4") and width 1.09mm: the flaws looked upon can be cracking, thinning, corrosion buildup... To keep up a good tradeoff between accuracy and speed inspection, EDF started using an inside tube array probe. Generic information on array probes on steam generator tubes can be found in reference (1). A picture of an array probe is shown in Figure 1.

In EDF standard, each steam generator tube is inspected in line with a calibration tube containing artificial flaws allowing for standardization of probe signals and checking of its functionality. The array probe being sensitive to off-centering, a typical solution to limit off-centering effect on the calibration phase is to use two different calibration flaws: 30% outside groove for amplitude setup and dimensional variation for phase
setup. The goal of this paper is to present further signal processing treatments allowing an even more robust calibration to off-centering noise.

Figure 1: pictures of the inside tube array probe used on steam generators: general view (top) and zoom on the pancakes which constitutes emitter to receiver sensors. Off-centering noise origin can be the ageing of the plastic “tulips” used to maintain the probe in the middle of the steam generator tubes.

We start in section 2 by introducing the Eddy Current array probe, the calibration tube and the off-centering noise. Then, in section 3, we derive a mathematical model for the recorded signal on the array probe affected by off-centering noise: we start with a model assuming the probe is calibrated and then extend it to the general case of raw data. This model allows the derivation of a filter which suppresses the off-centering noise, which we subsequently use in order to estimate the optimum calibration coefficient. Finally, we explain how to reconstruct an optimally calibrated signal and we briefly compare it to the original one on the calibration groove. In section 4, a conclusion ends the paper.

2. Array probe, calibration process and off-centering noise

2.1 Array probe and multi-frequency signal analysis

Tubes to be inspected are made of Inconel, with outside diameter 19.05mm (0.75”) and width 1.09mm. The inside diameter is 16.87mm (0.664”). EDF uses an inside tube array probe which consists of 32 pancake coils, 16 on the circumferential and 2 rows of coils in the axial direction. The outside diameter of the probe is less than the inside diameter of the tube, and the gap tube/probe is filled by guiding pin commonly called “tulips” such as shown in Figure 1.

Every emitter to receiver couple is a sensor and those parallel to the tube axe are called axial channels while those perpendiculars to the tube axe are called circumferential channels. The probe injected signal is carried over by four frequencies ranging from 50 kHz to 400 kHz. At each frequency, these channels record complex signal which can be used in the temporal domain or in the Lissajou domain. In this paper we limit ourselves
to the 16 circumferential channels and the highest frequency \( F_1 = 400 \text{ kHz} \). We plot on Figure 2 the time and Lissajou representations of these 16 channels while the probe enters the calibration external groove called GLE30 and defined in the next paragraph. The sample rate on the tube axis is 2 points per mm. Real and imaginary components of the Eddy Current signals are also called X and Y components.

![Figure 2: probe signal at CF1 (M=16 circumferential channels, 400 kHz) when the eddy current probe enters the external groove used for amplitude calibration (GLE30). There is no off-centering noise in this acquisition. The left panel shows the X and Y components along 30mm of the tube axis (temporal representation) while the right panel shows the same signal in the Lissajou representation. On this time window, each channel can be associated with an amplitude/phase measurements associated with the two points separated by the maximum distance in the Lissajou domain: the amplitude average value over the 16 channels is 4.99V and 108°. The reference value used for signal quality check up is 5V \( 107° \pm 10\% \pm 10° \) as shown on the right panel with a black dashed line – the signal quality is good when all data extremity fill in that dashed diamond.]

2.2 Calibration process and probe signal quality check-up

The calibration tube represents the tubes to be inspected: identical alloy and dimensions. It contains three areas used for calibration and additional defects used for probe signal quality check-up. The three areas used for calibration corresponds to three steps of the calibration process:

a) a flawless part for electrical mean derivation,

b) an external groove of length 20\( \text{ mm} \) and depth 30\% of the tube width, called GLE30 in the following, for amplitude calibration,

c) and an expansion of length 25\( \text{ mm} \) and offset 500\( \mu\text{m} \), called VD in the following, for phase calibration.

These three calibration steps are a classic solution to limit off-centering effect on the calibration phase, because the off-centering noise and the offset associated with the expansion (VD) have almost identical phases.

For every emitter to receiver couple, the EDF calibration guideline fixes 5 Volt on the GLE30 and 0° on the VD. This implies that tube flaws located close to outside diameter
(called external flaws) will appear centered on the imaginary axe (their phases are close to 90°) while those close to the inside diameter (called internal flaws) will appear on the real axes (their phases are close to 0°).

The signal quality check-up is done with a comparison of the channels amplitude values over a calibrated flaw to a reference value, with an accepted variability of +/-10% and +/-10°. For the external groove GLE30, the reference value is 5V 107° and the accepted values are those that fall inside the diamond shape shown in Figure 2.

### 2.3 Off-centering noise signal and physical model

When the probe is ageing, it is affected by off-centering noise which arises from the fact that some of the sensors get closer to the tube while those at 180° (the extreme opposite) get farther from the tube. The distance tube/probe is thus varying along a sinusoid of unit period, and, with a first order approximation, we can assume that the Eddy Current record of this variation is also sinusoidal of unit period. We can verify this assumption by computing the spectrum density of the off-centering noise, see Figure 3.

![Figure 3: array-probe signal at CF1 on a flawless part on the calibration tube, but affected by off-centering noise. The left panel shows the X and Y components along the M=16 sensors and across 5mm on the tube axis (10 samples) while the right panel shows the Log Power Spectrum along the sensor space over 100 samples. The normalized frequencies range from -8 to 7. There is more than 20 dB difference between the first spectral line (period=1) to the others, meaning a decrease of 100 on the squared amplitude.](image)

The signal of Figure 3 being calibrated, we note that the off-centering noise is mostly on the real component (X component), which is consistent with our calibration standard which locates events affecting the inner part of the tube on the real component. The problem arising from off-centering noise does not concern the phase calibration step, because the expansion (VD) has a phase very similar to off-centering. On the contrary, the amplitude calibration is affected by off-centering noise, as exemplified by the left
panel of Figure 4 which shows a noisy acquisition over the GLE30 in the Lissajou domain.

In the next section, we introduce an additive mathematical model for the signal and noise mixture recorded in the array probe, in order to derive a robust calibration scheme.

3. Off-centering noise filtering and robust calibration

We start by introducing a mathematical model for an already calibrated array probe signal before moving to the general case of raw data. It is possible to assume an already calibrated model because the probes are regularly calibrated during a steam generator inspection and the off-centering noise increases with ageing.

3.1 Axisymmetric signal plus off-centering noise model

3.1.1 Scalar and vector models for a calibrated signal

Let us note:
- \( y_{m,n} \in \mathbb{C} \) the complex signal recorded on sensor \( m \) at time sample \( n \),
- \( a_n \in \mathbb{C} \) the amplitude of the off-centering noise (albeit the imaginary component should be very small when the signal is calibrated),
- \( x_n \in \mathbb{C} \) the axisymmetric electric signal associated with the calibration tube at time sample \( n \) (flawless part, GLE30 or VD),
- \( b_{m,n} \in \mathbb{C} \) the general noise contribution.

We then get the scalar signal plus noise model:

\[
y_{m,n} = a_n \cos \left( 2\pi \frac{m - 1}{M} + \phi_n \right) + x_n + b_{m,n}
\]

where \( \phi_n \in \mathbb{R} \) is the phase sinusoid which is assumed independent along the tube axis, and where \( 1 \leq m \leq M \).

While concatenating the 16 sensors in a column vector, and noting \( 1_M \) the M-vector column of 1, we get the following vector model:

\[
y_n = \Theta a_n + x_n 1_M + b_n, \quad \text{where} \quad y_n \in \mathbb{C}^M, \Theta \in \mathbb{R}^{M^2}, a_n \in \mathbb{C}^2, 1_M \in \mathbb{R}^M, b_n \in \mathbb{C}^M \tag{1}
\]

with \( \Theta = \begin{bmatrix} 1 & 0 \\ \cos \left( 2\pi \frac{M-1}{M} \right) & \sin \left( 2\pi \frac{M-1}{M} \right) \end{bmatrix} \) and \( a_n = \begin{bmatrix} a_n \cos(\phi_n) \\ -a_n \sin(\phi_n) \end{bmatrix} \)

3.1.2 Raw model

In the general case, the signal recorded on the array-probe is raw, meaning its vector mathematical model is:

\[
z_n = \mathcal{D}(c)y_n + d \quad \text{where} \quad c \in \mathbb{C}^M, d \in \mathbb{C}^M \text{ are respectively the unknown calibration coefficient and bias, and where } \mathcal{D} \text{ is the diagonalization operator.} \]
Although we did derive a joint Maximum Likelihood estimation of the unknown calibration coefficient and bias while minimizing the off-centering noise, we will stick to the calibrated model in this paper for simplification purposes.

### 3.2 Signal orthogonal decomposition and filtering

Going back to equation (1), one can easily compute the orthogonal decomposition:

$$ I_M = P_\Theta + P_{\Theta^\perp}, \quad \text{where} \quad P_\Theta, \quad P_{\Theta^\perp} \in \mathbb{R}^{M, M}, \quad \text{and} \quad P_\Theta = \Theta(\Theta^T\Theta)^{-#} \Theta^T = \frac{2}{M} \Theta \Theta^T \quad (2) $$

Where $I_M$ is the identity matrix, $(.)^#$ is the Moore-Penrose pseudo-inverse, and $(.)^T$ is the transpose operator. Under the assumption that the general noise component $b_n$ of eq. (1) is a white homogeneous complex circularly-symmetric Gaussian vector, this decomposition leads to both the Maximum Likelihood and the Least-Squares solution of the problem of subtracting off-centering noise from the received signal:

$$ \hat{y}_n = P_{\Theta^\perp} y_n \quad (3) $$

Equation (3) allows to suppress the off-centering noise without affecting the signal of interest if it is axisymmetric (harmonic of period 0 and 1 are orthogonal), but it would probably affect the probe response to a 180° circumferential flaw. Thus, in the next paragraph, we explain how to use it only to compute the optimum calibration coefficient.

### 3.3 Signal reconstruction for steam generator tube inspection

In order to use the filter on a real tube, we propose to use the orthogonal filter to derive optimum calibration coefficients: $\hat{c}_{\Theta^\perp}$ and $\hat{d}_{\Theta^\perp}$, while applying the process of §2.2 to the eq. (3). Then, a reconstructed signal for tube inspection can be:

$$ P_\Theta y_n + \mathcal{D}(\hat{c}_{\Theta^\perp}) \hat{y}_n + \hat{d}_{\Theta^\perp} \quad (4) $$

Indeed, using eq. (4) allows converging to a calibrated signal if the off-centering noise converges to zero. Even if the off-centering noise does not disappear, we can see on Figure 4 below that using our process greatly improve the calibration.
Figure 4: probe signal at CF1 in the Lissajou domain when the eddy current probe enters the external groove used for amplitude calibration (GLE30) while affected with off-centering noise. The left panel shows the standard signal while the right panel shows the signal reconstructed according to eq. (4). Without off-centering noise, the expected mean value would be 5 V 107° +/-10% +/-10° as shown by the dashed diamond. Comparing these figures enlighten that using the optimum calibration coefficient improve the noisy acquisition calibration.

4. Conclusions

In this paper is presented a novel approach to calibration of inside tube Eddy Current emitter to receiver array-probe such as used on French and American nuclear plants steam generators. Indeed, sometimes these probes suffer from off-centering noise arising from the ageing of its mechanical parts. Our approach is based on a first order model assumption that this noise is described along the sensor space as a sinusoid of unit period. Henceforth, we derive a Least Mean Square filter allowing the removal of the noise contribution without affecting the signal of interest in the calibration tube. The filter is actually an orthogonal projection and allows defining two parts: the estimated noise and the estimated signal. Firstly, we estimate the optimum calibration coefficient on the estimated signal part. Secondly, we reconstruct a signal from the original estimated noise part plus the newly calibrated estimated signal part (see eq. 4). In a future paper, we will present the global approach considering a raw signal.

References