IMPROVEMENT OF DETECTION OF SMALL DEFECTS LOCATED NEAR OR FAR FROM WELDS OF MAGNETIC STEAM GENERATOR TUBES USING REMOTE FIELD EDDY CURRENT

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Abstract

Using numerical software optimization, new remote field eddy current systems based on small multiple vertical and horizontal coils were build in laboratory to investigate smaller outer tube defect detection in ferromagnetic steam generator tubes of nuclear power plants. Small defects located on the outer tube surface as pinholes axial and circumferential notches are better visualized using the C-scan experimental data, even when these defects are located near weld zones and the inspection is done from the inside of the tube. Comparing with the classical system, based on Bobbin coils, the new system shows an improved detection and a better coping with the electromagnetic signal noise in the data arising from unknowns in the: weld structure (from electromagnetic point of view), probe wobbling during inspection, variation in the inner tube surface.

1. Introduction

In the in-service inspection (ISI) of the steam generator (SG) tubes of nuclear power plants, eddy current technique is widely used to inspect the SG tubes integrity. Assessment of their structural integrity is an important factor from both economical and safety point of view. In some special cases of nuclear power plants it is not possible to access the outer SG tube surface and all inspections should be conducted from the inside of SG tubes. While detection of the inner tube defects it is done more easily and could be supervised by a visual technique in the most difficult situations, due to the eddy currents attenuation in the tube wall the detection of outer tube wall defects depends mainly on the eddy currents probe geometry, sensitivity and operation frequency. In the special case when the SG tube has also ferromagnetic properties the remote field eddy current (RFEC) system is able to detect both inner and outer tube defects with relatively equal sensitivity [1]. The method was shown in the past that could also be extended to the inspection of austenitic stainless steel SG tubes [2].

Detection of smaller defects located outside of SG tube requires enhanced detection probes. Application of the RFEC technique to the detection of outer defects in ferromagnetic SG tubes poses several difficulties. These are related to the presence of defects in the vicinity of welds. Also, an important factor is the evaluation of signal versus noise ratio in the real time SG tube inspection. The source of noise can be: probe wobble, RF device speed, SG tube permeability noise, weld influence, etc. Systematic analyses of these effects were performed by the authors in the past using simulations software [3 - 5]. It was shown that weld signal do not change drastically as the weld distributions modifies or for small variations in the tube electro-magnetic properties. Also, variation of defect signal due to the speed effect increase drastically as the size of the defect is smaller and inspection speed is over 0.5 m/s.

In a previous work, the authors examined and optimized, using three-dimensional finite element simulations, the detection capabilities of smaller and multiple horizontal and vertical RFEC coils, disposed circumferentially inside of SG tube, and compared the results with the detection capabilities of a classical RFEC coil based on bobbin configuration [6]. The optimization procedure took into consideration only the defect sensitivity in a tube area, far from welds or support plates zones.

In the present paper, the new remote field eddy current multi-coils were built in the laboratory, based on the previously simulated data, and their detection capabilities were investigated for several electrical discharged machine (EDM) defects in ferromagnetic SG tubes as follows: axial and circumferential notches, pinholes and outer partial defects. The paper also examined the probe detection capabilities when the small defects were located near weld part, on the outer SG tube surface. The signal to noise ratio was evaluated by

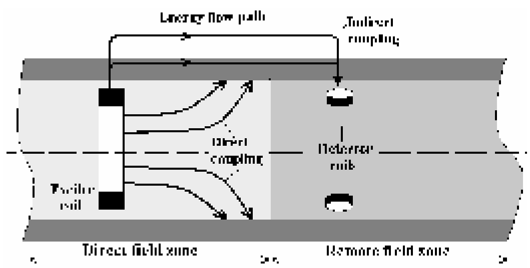
measuring the vibration noise signal in a free tube area.
Using the new RFEC multi-coil approach, a complete outer tube surface map was build (C-scan data) based on experimental measurements and the location of the outer defects could be better visualized, even when smaller defects are located near weld zones.

2. Remote field eddy current technique and experimental devices

Remote field technique is a well-established method to detect corrosion and wall losses in ferromagnetic pipes, using a low frequency eddy current technique, usually below 1 kHz [1].

Its principles, as described in Figure 1a, rely on the indirect electromagnetic coupling between the excitation coil system and detection coils. Contrarily to the classical eddy currents system, where both excitation and detection are closely located to each other, in the RFEC device the detection coils are completely separated from the excitation coils, and are located far, in the remote zone. The disturbance of the electromagnetic field lines due to the presence of an outer tube surface defect, shown in Figure 1b, can be sensed and measured with suitable detection coils located in the remote area.

The RFEC method is able to detect with relatively equal sensitivity both inner and outer defects in ferromagnetic SG tubes. The RFEC signal sensitivity depends on both geometry and size of the detection coils. The classical coil configuration of RFEC detection system, the Bobbin type, consists in two circumferential coils differentially connected, as shown in Fig. 2a. One of the challenges of the



a)

b)

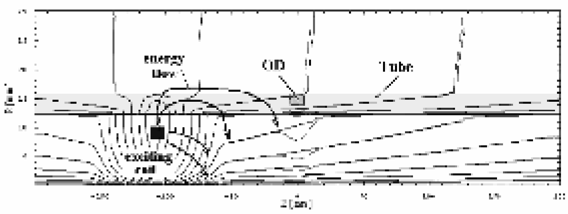


Figure 1*:* a) Schematic of the RFEC principle; b) RFEC flux lines distribution due to the presence of an outer defect in SG tube

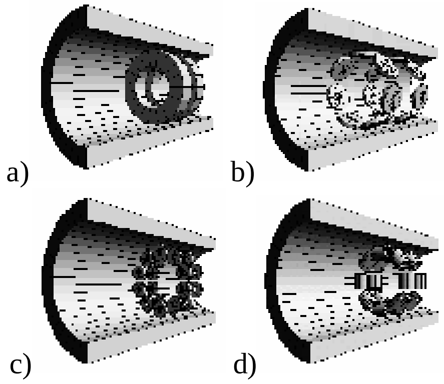


Figure 2*: RFEC detection coil types: a) Bobbin b) multiple horizontal; c) multiple vertical; d) multiple vertical II*

a)

b)

c)

Figure 3*: RFEC experimental device using: a) multiple horizontal coils; b) multiple vertical coils; c) Bobbin coil*

ISI using eddy currents is to detect smaller defects situated on the outer surface of magnetic SG tubes. For this purpose, the authors designed, using three-dimensional simulation software [3] new detection coils system using multiple vertical and horizontal coils those configuration is shown in Fig. 2b-d. The coils can be connected differentially in circumferential, axial direction or in a mixed way. Finite element simulations showed a good detection capability for the both multiple horizontal and vertical coils types while the multiple vertical coil type II had a noisy signal and poor defect sensitivity due to the probe wobble. Also, by connecting the coils in differential way in the axial direction, the noise from probe vibrations, as it moves along tube length, could be minimized.

Based on numerical simulations several multi-coils probes were build as is shown in Figure 3a-b. In Figure 3c is shown a view of the classical Bobbin

Table 1: Parameters of the RFEC coils

RFEC detection coil type	*Inner/Outer diameter/ Length [mm]*	*Number of turns*	*Distance between coils*
Bobbin	17.5/19.5/3	900	1
Small horizontal	1/3/3	1000	1
Big horizontal	1/8/7	4000	7
Small vertical	1/3/3	2030	0.5
Medium vertical	1/5/2.5	7200	0.5
Big vertical	1/8/8	20000	0.5

system which consist in two circumferential coils connected in a differential way. The parameters of the optimized coils system are presented in the Table 1. Two multi-coil horizontal type and three multi-coils vertical type were designed by choosing different sizes of coils. Simulations showed that while smaller coils could better detect smaller defects, their signal amplitudes decrease and are more affected by probe wobbles. In the same time, as the probe size increases, a smaller number of coils could be fitted in the limited space inside of the tube, resulting in a poor covering of the tube surface and decreased small defect sensitivity. The optimum coil configuration is a balance between all these elements as well as the inspection frequency and tube geometrical parameters.

3. Filtering algorithm for C-scan data

The C-scan data consists of RFEC signal from multi-coils probes as they move along tube length. During multi-coil movement along tube length, their signal is affected by several noises those sources is represented by: unknown in the weld electromagnetic properties distribution, variations of the inner SG tube diameter, variations in the probe speed during movement, electronic noise and others. In most of the cases the noise signal is correlated with the defect signal. The noise in the data is filtered using an algorithm based on the Fourier transform, as is explained in the following.

Let's denote with S_0 the original C-scan data, which consists in a two-dimensional array, those values depends on the i_{th} step of the RFEC probe along tube length and the k_{th} step that represents the number of multi-coils in circumferential direction. The S_0 signal has two components, real (x_0) and imaginary (y_0), as is shown in equation (1). In order to remove the noise coming from probe vibrations during movement, the original signal S_0 is rotated by a constant angle α, whose value depends on tube magnetic properties and probe geometry. In the new rotated signal S_1 the vibration noise is separated on the x_1 real component, while the working signal is represented by the y_1 imaginary component, as is shown in equation (2).

(1)

(2)

In the next analysis, the noise signal x1 is completely discarded and the working signal is represented only by the y1 data. For every k_{th} step, a new signal y_2 is defined as the Fourier Transform (FT) of the y_1 as is shown in equation (3). The phase ϕ of y_2 signal is defined in equation (4), while the signal amplitude A is decreased by a constant value ε, which control the filtering method. By varying the values of ε, the signal is filtered, and the frequency of the irregular pattern arising in the data is removed. The new filtered signal y_3 is constructed in equation (5).

(3)

(4)

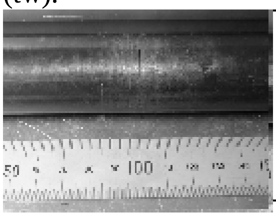
(5)

In equation (6) the data are transformed back to the time domain using the Inverse Fourier Transform (IFT). The final filtered signal S_1 is computed by subtracting from the initial y_1 signal the real part of the regular pattern represented by y_{40}.

(6)

4. Detection of defects located in a tube free weld area

Several small defects, as, circumferential notch 0.5 mm wide, and pinholes 2-5 mm diameter, were machined, using an electro discharged apparatus, in two ferromagnetic SG tubes made on 2.25Cr-1.0Mo allow. The characteristics of the defects are presented in Table 2. The SG tube wall thickness is 3.8 mm and the depth of the defects is presented in relative percentage from the tube wall thickness (tw).



b)

Figure 4*: Outer SG tube defects: a) pinhole 1mm diameter; b) circumferential notch 0.3 mm wide, 10 mm long*

Table 2: Parameters of the defects in SG tubes

Nr.	*Defects description*
Tube 1	Outer pinhole 50%tw, diameter = 2, 3 and 5 mm
Tube 2	Outer circumferential notch 0.5 mm wide, 10 mm long, depth = 50%, 75% and 90%tw

In the multiple coil configurations, only two coils, differentially connected, were prepared, as was shown previously presented in Figure 3a-b. The signal from the pinholes, machined in Tube 1, was measured using all five multiple coils configuration as well as with a classical Bobbin coil type detection system, as is shown in Figure 5. The signal is represented only by a line data, recorded as the probes moves along SG tube length. During measurements with multiple coils configuration, the small defects were positioned right under the two small coils. In order to evaluate how vibration noise compares to the defect signal the experimental signal from vibrations of both excitation and detection system in a tube area without defect were recorded and labeled as “Noise X” and “Noise Y” corresponding to the vibrations in X-horizontal and Y-vertical direction, respectively. In the second step, the complex representation of the RFEC signal was rotated that vibration noise has maximum amplitude on 1^{st} channel and the defect signal is more visible on the 2^{nd} channel. In the third step, the information from the 1^{st} channel was removed and the signal from 2^{nd} channel was filtered using the algorithm earlier described.

In spite of that multi-coils type “big horizontal” and “big vertical” has a better S/N ratio their signal is more affected by the noise coming from the variations of the inner tube diameter. Measurements, using Bobbin type coil, showed that vibration noise is small, but the signal from defect is also very noisy due to its small signal amplitude and increased amplification noise from the electronic amplifier system. Small pinhole 2 mm diameter can

Figure 5*: Experimental measurements of detection of outer pinholes in SG Tube 1 using Bobbin and multi-coil horizontal and vertical system*

be detected only using the multiple coil configurations, especially medium vertical coil type. The horizontal multi-coils detection is more sensitive to the probe wobbling, as it can see in Figure 5. Further experiments [6] showed that small circumferential notches from Tube 2 and axial notches are also best detected using the multi-coil approach.

The main limitation in using the classical Bobbin coil configuration is that, during experimental measurements, only one line scan is available. However, using the multi-coil approach, more data are available and consequently more information could be gather about noise signal structure and the proper algorithm which can be used to remove it. The multi-coil signals, using only "medium vertical" type were recorded initially by scanning the tube multiple times with an angular angle of 20^0 degrees. Further analyses showed however that the C-scan data still has a very good resolution even when the angles between multi-coils in circumferential direction increases to 40^0 degrees and during scan, the small defect is located circumferentially between the two coils.

In Figure 6 is presented a C-scan of the raw experimental data, recorded using multiple coil "medium vertical" type to detect outer pinhole 5 m in diameter and depth 50%tw. The noise amplitude level is small compared with the defects signal and the defect location is easily visualized on the tube surface signal map.

Figure 6*: C-scan of the outer tube surface for detection of outer pinhole 5 mm diam., 50%tw*

a)

b)

Figure 7 *C-scan of the outer tube surface for detection of outer pinhole 2 mm diam., 50%tw: a)raw data; b) filtered data*

Figure 8*: C-scan of the outer tube surface for detection of circumferential notches 10mm long, 0.5 mm wide and depth 50%, 75% and 90%tw*

In Figure 7a is shown the C-scan of measurements data to detect an outer pinhole 2 mm in diameter and depth 50%tw. Due to the smaller defect size, the signal amplitude is small and the noise structure has a regular pattern whose frequency can be cut using the algorithm presented earlier. The filtered signal is presented in Figure 7b, which shows a better visualization and detection of this defect.

Experimental detection of circumferential notches in Tube 2, is shown in Figure 8. The signal/noise ratio is very good, and even for detection of notch with depth 50%tw no signal processing is necessarily to further enhance the image and decrease the noise.

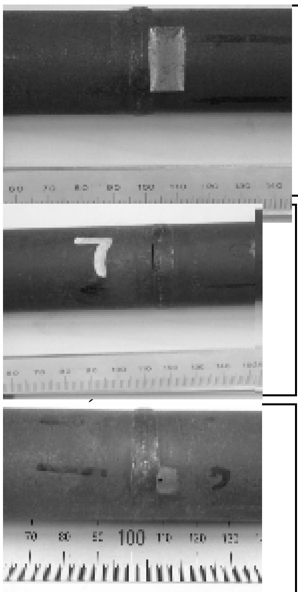
5. Detection of defects located near weld in HAZ

Experimental measurements confirmed the good sensitivity of the multiple-coils "medium vertical" types, in detecting small defects on the outer SG tube surface. However, near welds zone, in the transition area between weld and base material, known as heat-affected zone (HAZ), material inhomogeneities and gradients in the mechanical properties influences the material electromagnetic properties. Under thermal and corrosion stress, smaller defects are more likely to initiate and grow in this zone. Detection of these defects is more difficult due to the weld signal that can hide the defect signal and it is considered in this case as supplementary noise data.

Several small defects, as outer partial, circumferential and axial notches 0.3 mm wide, pinholes 1-3 mm diameter, were machined in ferromagnetic SG tubes, near weld area, as is shown in Figure 9. Their parameters are listed in Table 3. The width of the weld is 5 mm while the HAZ length was estimated to be another 5-7 mm next to the weld.

Table 3: Parameters of the defects machined near weld in SG tubes

Nr.	*Defects description*
Tube 3	Outer partial, 10 mm wide, depth 75%, 90%tw
Tube 4	Outer circumferential notch 0.3 mm wide, 10 mm long, depth = 75% and 90%tw
Tube 5	Outer axial notch 0.3 mm wide, 10 mm long, depth = 75% and 90%tw
Tube 6	Outer pinhole 1 mm diam., 95%tw Outer pinhole 3 mm diam., 75%tw
Tube 7	Outer pinhole 3 mm diam., 30%tw Outer pinhole 3 mm diam., 50%tw



c)

e)

Figure 9*: Outer SG tube defects near weld in HAZ: a) outer partial; b) circumferential notch 0.3 mm; c) axial notch 0.3 mm; d) pinhole 1 mm diam; e) pinhole 3 mm diam.*

The weld signal, was analyzed in the past, using two dimensional simulation software, and was shown that different distribution of the weld electromagnetic properties do not change significantly its signal [5]. Using the Bobbin coil, the weld signal without defect was measured in two cases, presented din Figure 10a and in other two different situations shown also in Figure 10b. The signal from different welds is indicated using continuously and dashed lines. It can be seen that if there is a defect next to weld, in order to be detected its signal should be higher than the weld signal or with a different phase. However, because the weld has a full circumferential geometry, the RFEC device based on Bobbin type its less sensitive if a small defect is located next to weld, which is illustrated in the following. Variations up to 30% of the weld signal amplitude were observed, while the weld signal phase remained relatively constant, even if the weld was measured in different tube samples. The variations of the weld signal amplitude are mainly due to the variations in the geometrical size of the welds and less due to variations in weld electromagnetic properties.

Bigger outer partial defects (Tube 3), 75% and 90%tw, 10 mm wide are easily detected using Bobbin configuration as is shown in Figure 10 c-d. However, detection of circumferential (Tube 4) and axial (Tube 5) notches is difficult, even if their

a) b)

c) d)

e) f)

g) h)

Figure 10:*Experimental measurements using Bobbin coil: a-b) weld signal; c-d)weld and outer partial e) weld and circumferential notch; f) weld and axial notch; g-h) weld and pinhole*

depth is 90%tw (see Figure 10 e-f). The amplitude of pinholes signal (Tube 6-7) is also smaller than the weld signal, as it can be seen in Figure 10 g-f.

The main difficulty in detecting small defects located near weld, using Bobbin coils, is due to the fact that the Bobbin coil is sensitive to the all full circumferential weld geometry and the signal from small defect has usually smaller amplitude than weld signal; as was shown in the previous figures. Also, it is not possible to use the defect phase information, since its phase is similar to the weld signal phase. Only big outer partial defect, 10mm wide and depth 75%tw could be detected near weld using the Bobbin coils system.

Figure 11*: C-scan of outer partial defect near weld*

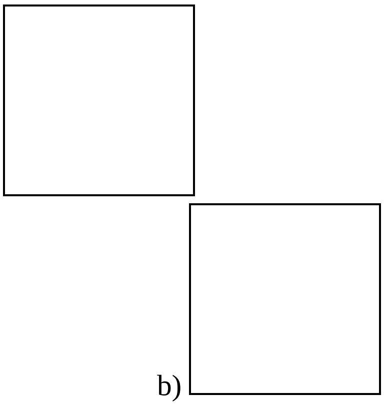
a)

b)

Figure 12*: C-scan of outer pinhole 3mm diam., 50%tw near weld: a) raw data; b) filtered data*

The next analysis is focused on the detection of small defects (described in Table 3) using the multiple coil “medium-vertical” system. Figure 12a shows the C-scan measurements data of detection of an outer pinhole 3 mm in diameter and depth 50%tw. The pinhole signal is visible near the weld signal, on the surface plot, but there are also noise in the signal due to coils wobbling and variations in the inner tube diameter. Using the filter, pinhole signal is enhanced. The defect signature consists in two closely related peaks with opposite colors. Also, the weld signature is a band-like all along tube circumferences.

A most difficult situation is represented by the detection of the outer pinhole 3 mm in diameter and depth 30%tw near weld. The data are shown in



a)

b)

Figure 13*: C-scan of outer pinhole 3mm diam., 30%tw near weld: a) raw data; b) filtered data*

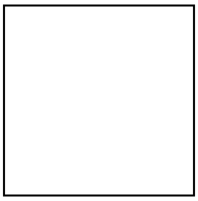
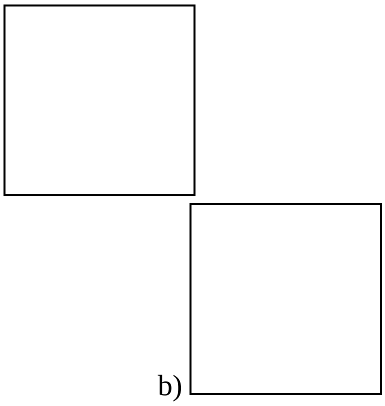


Figure 14*: C-scan of outer pinhole 1mm diam., 95%tw near weld (filtered data)*

Figure 13. Using the raw data, it is impossible to guess the defect location. However, after filtering, the defect position is again clearly indicated next to the weld line.

The defect signal is proportional also with the volume of the defect. As the defect size decreases, it can be detected if its depth is bigger. The main point is to detect smaller defects before they penetrate the tube wall. In Figure 14 it is shown the C-scan detection of a pinhole only 1 mm in diameter but with depth 95%tw. This could also be visualized only after the filter was applied.

Small axial and circumferential notches (Tube 4-5) with depth 75%tw near weld are better detected using multiple coil system. As, is it can be seen in



a)

b)

Figure 15*: Raw experimental data of C-scan of defect near weld: a) circumferential notch 75%tw; b) axial notch 75%tw*

Figure 15, in both cases the defect signal amplitude has big amplitude, and it is not necessarily to use the filter to identify these defects.

There are several reasons why the multi-coil system is more sensitive to small defects near weld.

The first one is that one coil from of the multi- coil system is sensitive not to the all weld geometry but only to a limited area, spanned around coil. This is why, if there is a small defect near weld, even if its signal is small, it can still compare well with the weld signal and the signal/noise ratio has higher amplitude than the case when Bobbin coil system was used.

The second reason is due to the fact that more data are gathered during inspection of tubes, and using the C-scan data, more information is available about noise structure pattern, which could be better exploited by designing a filtering technique able to remove it, without side effects on the defect signal.

6. Conclusions

Detection of smaller outer defects in ferromagnetic steam generator tubes, using eddy current technique, was improved by using a multi-coil vertical system approach. Experimental measurements were consistent with the predictions during simulations design, showing a good detection capability for multi-coil vertical system. For smaller sizes of the coils, both horizontal and vertical multiple coils have similar S/N ratio. As their size increases, multiple vertical coils have a smaller vibration noise and also their signal is less affected by the regular variations of inner tube radius. Small defects located on the outer tube surface, as pinholes 1 mm diam. and depth 95%tw or 3mm diam and depth 50%tw and axial or circumferential notches 0.3 mm wide, 10 m long and depth 50%tw can be detected even when are located near weld area, by using a filtering technique based on Fourier Transform.

7. References

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