Simulation of eddy current testing of steam generator tubes with wears and secondary side magnetite deposits

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Abstract

Steam Generator (SG) tubes of Pressurized Water Reactors are prone to degradation and are periodically inspected with eddy current techniques. SGs provide a safety barrier between the radioactive primary side and the non-radioactive secondary side. Historically, a major degradation issue was stress corrosion cracking of tubes made of alloy 600. In modern SGs, a better resistance to stress corrosion cracking is observed with the replacement of alloy 600 by alloy 690. However, this alloy does not prevent tubes from wear at support locations or wear resulting from fretting with loose parts. Long-term operation of SGs leads also to non-volatile species accumulation in the secondary side of the SGs, mainly magnetite. Magnetite deposits may build up as dense and solid material on the top of the tubesheet (hard sludge) but also in the flow slots of tube support plates and therefore modify the general flow pattern and velocity of the secondary fluid. This effect has detrimental effects on the safe operation of SGs. The clogging-up ratio of the flow slots therefore needs to be assessed.
The development of an ECT simulation model to address tube wear and magnetite deposit in SGs is presented. This model is based on the CIVA NDT platform. A bobbin coil signal is simulated and its performance for tube wear and magnetite deposit evaluation is discussed.

1. Introduction

The safe operation of nuclear power plants (NPP) relies on a defence-in-depth approach which involves 5 independent levels of defence in order to reduce the consequences of a failure [(1)]. Non-destructive testing contributes to the first level (prevention of abnormal operation and failures by a conservative design and high quality in construction and operation) and the second level (control of abnormal operation and detection of failures by control, limiting and protection systems and other surveillance features).

In a pressurised water reactor, the tubes of steam generators are periodically inspected in order to assess their integrity and to prevent the occurrence of a tube rupture. A tube rupture produces a small breach in the primary coolant circuit of the reactor and could result in radioactive contamination in the environment. SG tube walls are thin, with a typical thickness value of 1 mm, and are subject to wear at support locations. SGs tubes made of alloy 600 are also prone to stress corrosion. Because of the active degradation mechanisms of the tubes during operation and the consequences of a tube rupture, it is important that in-service inspections are conducted with a high level of reliability and performance.

IRSN is a public expert body in nuclear safety and a technical support organization for the French regulatory body. In the process of safety assessments, IRSN may use modelling tools for the evaluation of NDT performance and for technical exchanges with the industry. In that respect, the simulation of NDT techniques gives the ability to quantify the influence of essential parameters on performance aspects such as detectability, repeatability and sizing accuracy. This approach is consistent with the qualification requirements according to the ENIQ(2) methodology and the RSEM code(3). The inspection by operators of steam generator tubes is based on eddy current techniques (ET). In the following paragraphs, the development of an ET model within CIVA is presented for the evaluation of the clogging-up ratio of tube support plates clogging-up ratio and for the detection and sizing of wear under anti-vibration bars.

2. Tube support plates clogging-up

Continuous monitoring of primary-to-secondary leaks led to three shutdowns at the Cruas NPP: unit 1 in February 2004 and unit 4 in November 2005 and February 2006. Analyses carried out by EDF, following the last two events, resulted in them being attributed to high-cycle fatigue of steam generator tubes due to flow-induced vibration.
The results of in-situ examinations initiated by the Cruas NPP operator showed that the flow holes of the uppermost Tube Support Plates (TSPs) were partially or completely blocked by corrosion products (4). This phenomenon is referred to in this paper as TSP "clogging-up" and is shown in Figure 1.
From a safety perspective, the TSP clogging-up in SGs has several consequences (5):

- Local increase of the secondary fluid velocity with a risk of tube rupture for small row U-bends unsupported by anti-vibration bars (AVB) due to fluid-elastic instability;
- A reduction of the circulation ratio with a risk of water level oscillations detrimental to primary temperature and reactivity stability;
- A reduction of the water mass inventory, detrimental to accident transients associated with a loss of feedwater;
- An increase on the loads on SG internals (TSP, tie-rods) in the event of fast depressurisation of the secondary such as the rupture of a main steam line (6).

The clogging-up of TSPs must therefore be periodically assessed and kept to acceptable values by minimizing the iron transport in the feedwater train using high pH secondary side chemistry. A chemical cleaning of the secondary side of the SGs may be performed if needed to keep the SGs in a safe domain during operation.

The most direct and accurate way of evaluating the clogging-up ratio is to perform a remote visual examination of the TSP flow holes. However, the remote visual inspection of the flow holes is difficult to perform because of the difficulty of introducing a video probe inside the tube bundle. The main access is the secondary man-way in the upper part of the SG. A limited number of tube rows of the upper most TSP can be inspected using this access. Additional access is provided by the hand holes located nearby the tube sheet which enables the inspection of flow holes from the lower TSP. The hand holes' locations depend on the type of SG.

In addition to remote visual testing, the eddy current inspection technique can be used to evaluate the clogging-up ratio making use of the ferromagnetic properties of the magnetite deposit and the sensitivity of an eddy current probe to its magnetic and conductive environment. EDF has evaluated the use of bobbin coil signals for this purpose [(7)].

In this study, we discuss the performance of bobbin coils for the assessment of TSP clogging-up. Our approach is based on the simulation of bobbin coil signals using CIVA. We consider a simplified geometry with an axisymmetric TSP and an axisymmetric distribution for the magnetite deposit (Figure 2). The values for the electrical conductivity and relative magnetic permeability of the TSP are derived from previous work on broached TSP [(8)]. The values for the electrical conductivity and the magnetic relative permeability of the magnetite are based on expert elicitation. Several publications describe the geometry and mechanisms of magnetite deposit at TSPs [(9) (10)]. The usual distribution of magnetite in operating SGs is concentrated at the lower edge of the TSPs. A simplified distribution of magnetite located solely at the lower edge of the TSP is presented in Figure 3. The reference signal for the bobbin coil operated in differential mode and passing the TSP is plotted in black. The simulation result when a simple magnetite deposit is located at the lower edge of the TSP is given in red. A significant distortion of the signal can be attributed to the magnetite build up and may be processed to evaluate the level of clogging-up of the blockage ratio. The Blockage Ratio (BR) is defined as the ratio of the obstructed surface over the design surface of the water flow around a tube at a TSP location.

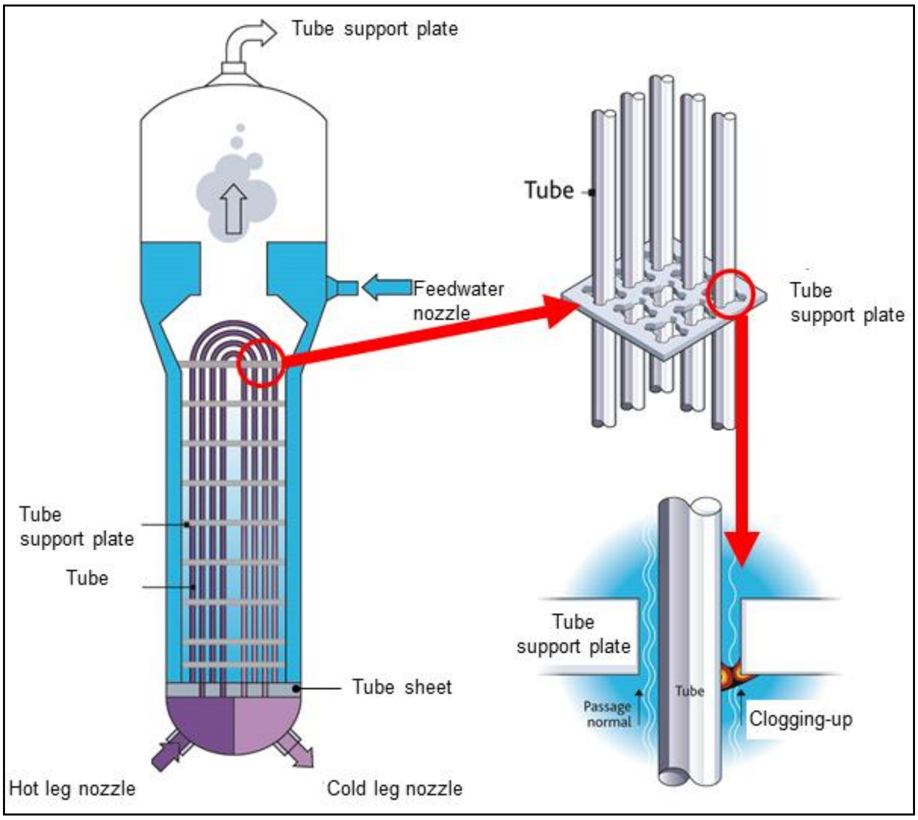

Figure 1. Tube support plate clogging-up. Corrosion products may build up in flow holes and modify the flow distribution (simplified deposit geometry).

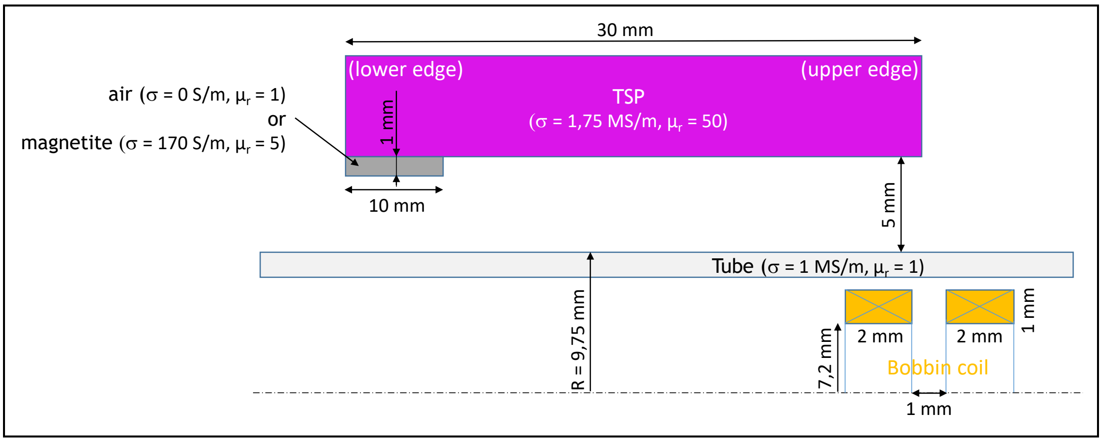

Figure 2. Simplified geometry for the simulation of bobbin coil signals for axisymmetric TSP with axisymmetric magnetite clogging-up.

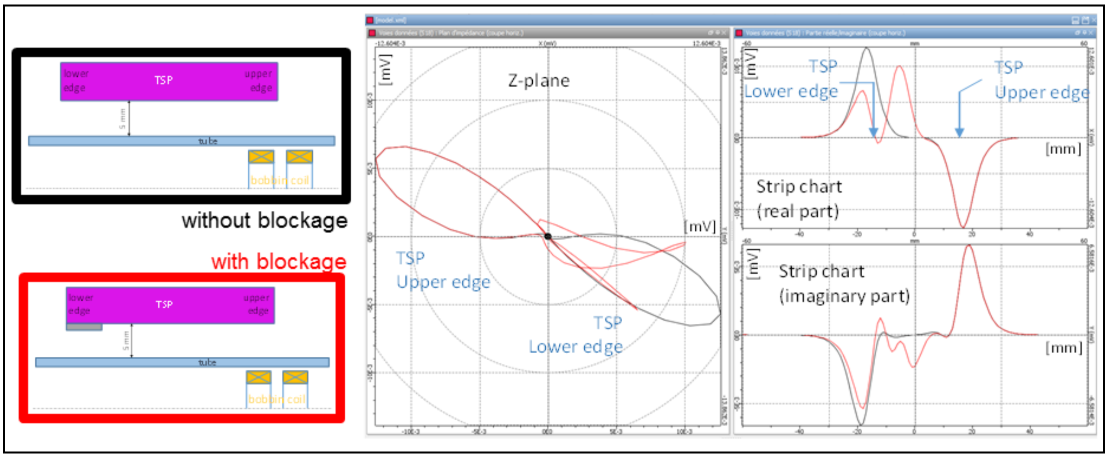

Figure 3. Simplified distribution of magnetite at the lower edge of the TSP. The magnetite deposit is located only on the TSP and induces a distortion of the EC signal (in red) compared to the reference case (in black) without deposit.

In Figure 4, the bobbin coil signal is computed for two deposit distributions with significantly different blockage ratios. In red, the relative permeability is 3 and the blockage ratio is 48%. In green, the relative permeability is 5 and the blockage ratio is 31%. The variation in the relative magnetic permeability could stem from a variation in the density and/or in the chemical composition of the deposits, e.g. copper or aluminosilicate which are likely to occur in operational SGs due to variation in the secondary water chemistry. The bobbin coil signal is similar for these two different deposit configurations. This example points out that although the bobbin coil is sensitive to magnetite build up at the TSP location, it is difficult to use it only for one channel in differential mode to evaluate quantitatively and reliably the blockage ratio. The use of other channels including absolute modes may be considered in order to derive a robust indicator of the blockage ratio as well as inspection with rotating probes [(11)].

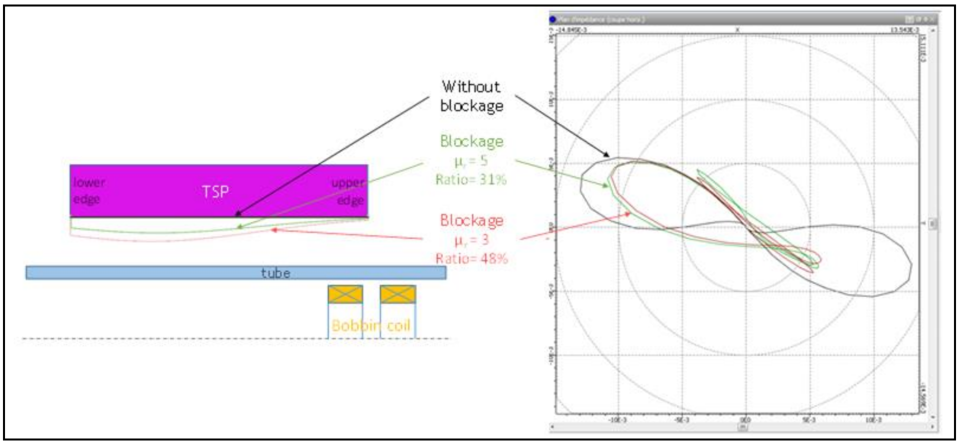

Figure 4. Examples of two different deposit distributions and blockage ratios (in green 31% and in red 48%) leading to similar signals.

3. Wear under anti-vibration bars

The design of SGs has been improved over decades of accumulated experience from operators. The choice of alloy 690 TT by some manufacturers proved to be a good choice with respect to resistance to stress corrosion cracking (SCC) in primary water and secondary environments although some research works point out some sensitivity to SCC in a secondary environment polluted by lead or sulfates [12].

Unfortunately, not all the degradation mechanisms observed in SGs have been answered by modern design SGs. For instance, tube wear still threatens the integrity of SGs. It can occur from loose parts [13], from tube-to-tube wear [14] and from tube-to-AVB wear [15].

A model for tube wear has been developed within CIVA by CEA in the framework of a collaboration with IRSN. Its purpose is to have the ability to analyse the influential parameters on eddy current signals using numerical experiments.

In this paper, we discuss some influential parameters for wear under AVBs which may be detected and characterized with the bobbin coil inspection technique. The definition of the parameters is done in a plug-in with a specific graphic user interface shown in Figure 5. The main parameters are: the wear depth and smoothing of edges, the AVB geometry, orientation, material and distance to the tube, and the radius of the tube.

In the following examples, the parameters considered for modelling the inspection configuration are given in Table 1. The validation of the model is based on a comparison with experimental data and is presented in Table 2.

The calibration is done both for experimental data and simulated signals with a reference flaw composed of four through-wall holes with a diameter of 1 mm and located 90° apart on the same section of the tube. The differences observed between calibrated experimental and simulated signals are less than 5% in amplitude and less than 5° in phase which is considered acceptable for the authors considering the noise level usually observed in eddy current testing.

Table 1. Parameters used to model U-bend inspection with the bobbin coil

Parameter	Value
Tube outer diameter	19.05 mm
Tube wall thickness	1.09 mm
U-bend radius (when applicable)	75 mm
Tube conductivity (alloy 690)	0.87 MS/m
Tube magnetic relative permeability	1
Bobbin coil outer diameter	14.8 mm
Bobbin coil inner diameter	14 mm
Coil height	2 mm
Coil number of turns	45
Gap between the two coils	1 mm
AVB width	4.6 mm
AVB height	12.36 mm
AVB conductivity	0.97 MS/m
AVB magnetic relative permeability	1
Frequency	280 kHz

Table 2. Validation of the model by comparison with experimental data

	Amplitude Difference (%)	Phase Difference (°)
4 through wall holes ∅1 (reference flaw)	**0**	**0**
Internal Groove 10%	1.3	0.1
External Groove 40%	3.4	4.6
Large External Groove 30%	0.7	4.3
Straight Wear 20%	4.8	3.9
Straight Wear 40%	4.5	4.8
Straight Wear 60%	3.7	4.3

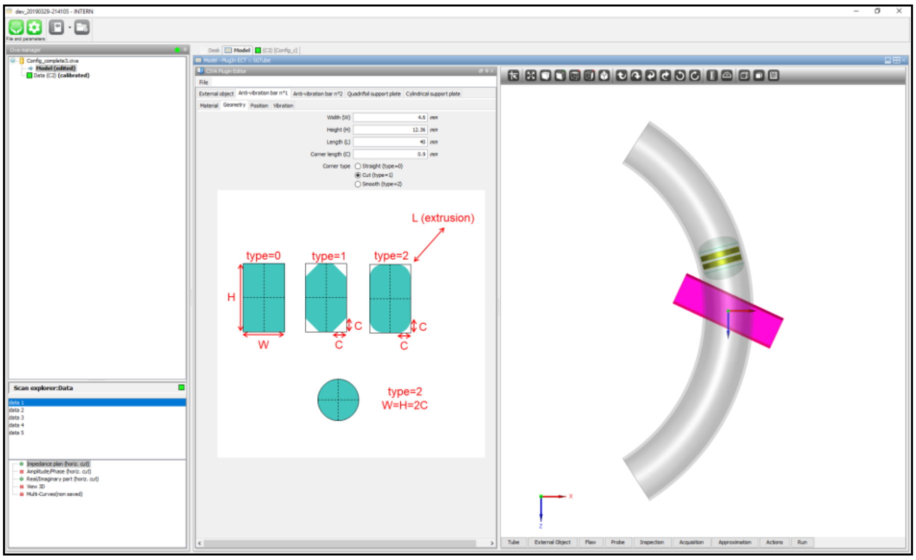

Figure 5. CIVA plug-in for the simulation of tube wear under AVBs. Several parameters define the configuration (AVB geometry and orientation, wear depth, U-bend radius).

The orientation of the AVB and the radius of the tube have been investigated and are presented in Figure 6. As can be seen from the bobbin coil Lissajous signal plotted on the right, the effect of these parameters is weak. It is negligible in amplitude and phase. Only a small distortion of the shape of the signal is noticeable and would be difficult to detect with noisy experimental data.

The effect of the tube-to-AVB gap is significant and is presented in Figure 7. For eddy currents, the effect of the AVBs and the tube wear have opposing effects. The AVB can be seen as an additional conductive material near the tube and the tube wear on the contrary is a lack of conductive material in the tube wall. These two effects are in competition and it can be observed from the Lissajous figure that a significant reduction of -41% in the signal amplitude occurs when the AVB is located inside the wear and nearly in contact with the tube wall with a negative gap of 0.4 mm with respect to the nominal tube wall.

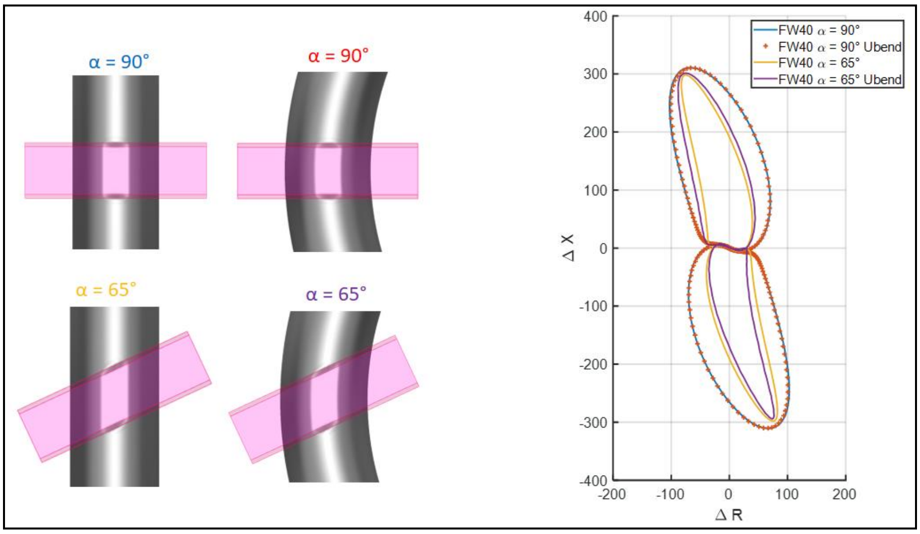

Figure 6. Analysis of the tube radius and AVB orientation on the bobbin coil signal.

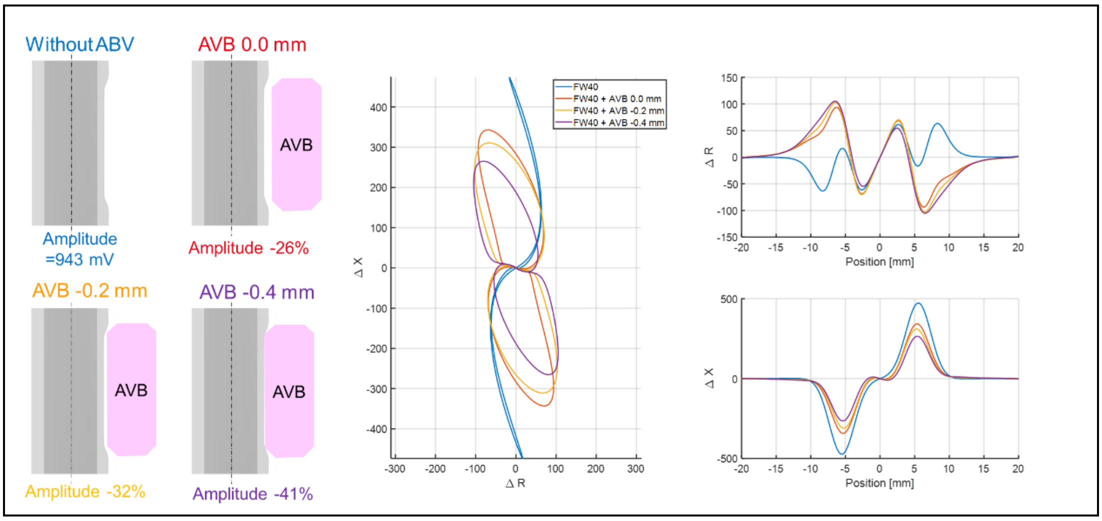

Figure 7. Effect of the tube-to-AVB gap on the bobbin coil signal for 40% through wall wear. In blue, without an AVB, in red an AVB and a 0 mm gap (AVB in contact with the tube without wear), in orange and purple -0.2 mm and -0.4 mm gap (AVB going inside the wear).

The effect of two-sided AVB wear versus one-sided AVB wear has been investigated by simulation. The bobbin coil is sensitive to flaws over all the circumference of a tube and cannot establish if a signal results from a single flaw or from multiple flaws. Simulation results for single-sided wear with depths ranging from 40% to 60% through-wall are compared to two-sided wear with a depth of 40% in Figure 8. The amplitude of two-sided wear of 40% is approximately equivalent to single-sided wear of 54%. Therefore, for a conservative assessment of the wear depth based on amplitude measurement, the single-sided wear should be considered. It is however interesting to quantify the conservatisms of this approach when applied to a two-sided wear situation.
The examples presented in Figure 7 and Figure 8 shows significant influences of two parameters. Several others parameters may have also a significant effect on the signal.

The combinatorial approach needed for qualification purposes might be costly and unpractical if based solely on experimental means. The worst case scenario might also be difficult to reach from a limited number of experiments. Therefore, the simulation of eddy current signals may conveniently complement experimental tests for qualification purposes.

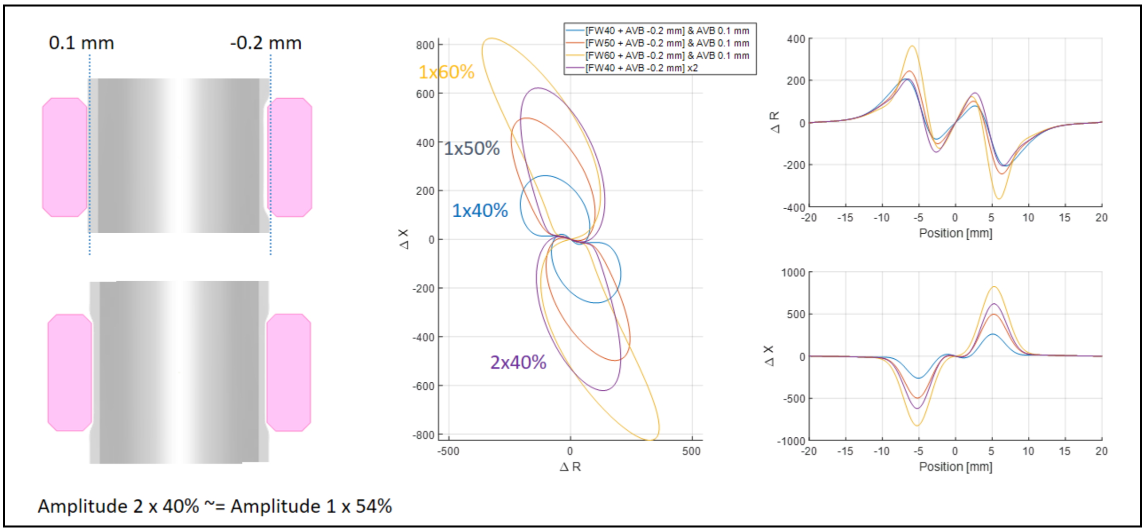

Figure 8. Analysis of the effect of one-sided wear of depth ranging from 40% to 60% versus a double-sided wear of 40%

4. Conclusions

In the nuclear industry, reliable in-service inspection of pressure vessels is required and should also be a continuous improvement process with respect to the defence-in-depth approach. The best available techniques should be used and the performance should be documented by a qualification process. The qualification methodology includes a review of the essential parameters which may prove to be very demanding in time and mock-ups if based solely on an experimental approach. A sensitivity analysis of the essential parameters can be based on simulation and may be used to optimize the number of experimental tests as well as providing physical reasoning on the performance and limitations of an NDT procedure.

IRSN is a technical support organization for the French regulatory body and carries out research in non-destructive testing to improve its skills and expertise in this activity. The development and validation of models for the simulation of in-service inspections is used to analyse and discuss NDT performance in detection and sizing. The aim of this research is to enhance IRSN capability to conduct independent assessments of industrial inspections.

In this work, eddy current simulation has been applied to discuss the performance of the bobbin coil inspection technique for the evaluation of TSP clogging-up and wear under AVB. The quantitative evaluation of the TSP clogging-up ratio based on the use of one bobbin coil differential channel may be associated with large uncertainties since different clogging-up ratios may results in similar eddy current signals. The use of additional frequency channels, absolute modes or rotating probes may be tested to obtain a more reliable assessment of the SG clogging-up ratio.

For tube wear under AVBs, a new CIVA plug-in has been developed by CEA and validated for some experimental setups. This model has been used to investigate the effects of some influential parameters on the detection and characterization of wear. The tube-to-AVB gap is an important parameter and a significant reduction in the signal amplitude is observed when the AVB is positioned inside the wear volume in close contact to the tube. A penalization configuration with the AVB in contact with the tube should be considered for a conservative assessment of the detection ability and sizing accuracy. The bobbin coil is sensitive to the average wear area around tubes and cannot establish if a signal comes from a one-sided or a two-sided wear. In this case also, a conservative approach should consider a deeper one-sided flaw and simulation may be used to evaluate uncertainties and conservatisms.

IRSN has supported the development and validation of NDT simulation tools dedicated to nuclear applications within the platform CIVA in the framework of a long-term partnership with CEA. These tools are used by IRSN to discuss the performance and conservatisms of NDT procedures with the industry, in particular new procedures which are not yet qualified or procedures which are not mandatory to qualify such as the inspection of SG TSPs for clogging-up evaluation. These tools may also benefit all NDT stakeholders and enhance the overall reliability and confidence in inspections.

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