ABSTRACT

Flow induced vibration wear has been detected in nuclear power plant steam generator tubes at the location of the anti-vibration bars (AVBs) and at tube midspans. In extreme cases, this can lead to a primary coolant leak and compromise plant operability (Figure 1). Excessive vibration can be caused by a number of factors - one of which is the uncontrolled gap between the tubes and the AVBs. Since there is no direct access to this area of the steam generator AREVA developed two non-destructive-examination (NDE) techniques to measure this gap. One technique is based on the eddy current (ET) method, which is a standard NDE inspection method for SG tubing, and the other is an ultrasonic (UT) method, known to provide very high accuracy distance measurement. Surface riding ET is used to rapidly measure a large number of AVB gaps and immersion UT is compared on a sample of these measurements to validate the ET calibration. The measurements derived from these inspections allow AREVA engineers to assess the condition of the SGs, validate models of the SGs operation and justify remediation actions necessary to arrest or limit further vibration related wear and continued operation of the plant. This paper explains the development and qualification of the techniques and discusses typical site implementation.

INTRODUCTION

Replacement steam generators are frequently designed to support higher megawatt power uprates. This is also true for older steam generators that have had design modification to increase plant power. Since the higher power generators must fit generally within the same space of the older generators, this typically implies higher steam flows and in some cases, higher primary flows. In some cases, tube to tube and tube to AVB wear has been detected by eddy current inspections. In extreme cases, the wear can lead to a through-wall leak that can compromise the safety of the plant.

Figure 1: AVBs are placed at strategic locations within the SG - particularly in the U-bend area above the tube support plates (left). Excessive vibration can lead to tube wear against the AVBs and against other tubes (right).
The primary suspected wear cause is Fluid Elastic Instability (FEI) initiated and promoted by several factors including (Ref 1, 2, & 3):

- High concentration of steam with fewer and smaller water droplets available to dampen vibration in localized area of tube bundle
- Gaps between the tube and AVB not within design specification resulting in
  - High vibration due to lack of tube restraint at AVB
  - Ineffective AVB “contact force” to stop motion
- Too perfect manufacturing practice resulting in a lack of any side preload between the tubes and their supports

To aid in analysis of these issues and to design and verify mitigation measures for steam generators with premature wear indications, it was desirable to measure the gaps between the tubes and the SG’s AVBs. This region of the generator is not readily accessible from the secondary side. Hand-hole openings are available or can be cut to access the periphery tubes but this only provides a limited view of the tube-AVB spacing. The only practical approach for large-scale measurement of these areas is by remotely measuring the gap from inside the SG tube. This same approach is used for the primary inspection of the tubes for cracks, wear, and other degradation and a significant amount of technology has been developed for rapidly inspecting these tubes in compliance with code and regulatory guidelines. An expansion of traditional eddy current and ultrasonic methods to address this gap measurement is a natural approach for this challenge.

**BOBBIN EDDY CURRENT**

Bobbin eddy current inspections are the most common form of tube inspection. With AREVA’s AIDA automated analysis package, the location of AVBs can be mapped automatically (Figure 2). The presence or absence of the AVBs are detected by a change in the low frequency eddy current response. When there is additional conductive material closer to the tube, there is a larger eddy current response. When the AVBs are further away or as in some cases that have been observed, the AVBs have been dislodged or eroded away, the voltage response is significantly reduced or nonexistent. Moreover, if the AVBs are skewed with respect to the tube, this can be detected by the bobbin coil (Figure 3). The bobbin probe however presents an aggregate response to AVBs on either side of the tube. It is not readily possible to separate the signal from each AB. If the tube wall is thinned from wear, this type of signal also influences the AVB signal and cannot be separated.

![Figure 2: AVB locations can be automatically registered with AREVA's AIDA software from the bobbin eddy current data as part of a normal inspection.](image-url)
A single pancake coil or a pair of pancake transmit/receive coils have a similar response to the presence of metal as the bobbin probe but in a more local sense. The rotating probes are inserted into the tube then pulled while rotating to produce a helical scan of the area of interest. The presence of metallic AVBs produces a measurable local voltage response. The response to each AVB is measured separately. Thus the terrain plot of the rotating probe response can be evaluated for the distance between the tube wall and the AVB on each side of the tube separately (Figure 4).

Figure 4: Rotating and array probes measure the local combined signals from AVB proximity and tube wear.

An array probe produces essentially the same response except that instead of one coil or a single pair of coils, the array probes have 36 or more coils arranged around the circumference of the probe. These coils typically are slightly further away from the tube ID wall and they are calibrated as a group. This may explain why the array probe is capable to quantify the gap with the threshold of 0.004” (0.01mm) and the resolution of 0.002” (0.05mm) while the RPC is capable to quantify the gap with the threshold of 0.002” (0.05mm) and the resolution of 0.001” (0.025mm). The array pull speeds however are up to 1m/second or more compared to a few mm/second for the rotating probes. Array probes can achieve inspection rates of 15-35 tubes per hour per probe compared with the MPRC rate of 4-10 tubes/hour per probe. In some cases, two or more probes can be placed in play within a single generator to accelerate the overall inspection speed.
Both the rotating and the array probes however are similarly sensitive to the aggregate effect of wear and the presence of the AVBs. Simplistically speaking, it is difficult to separate signals from the loss of metal associated with tube wear from the addition of conductive metal close to the coils associated with the close proximity of the AVBs. The calibration curve for AVB gap is substantially different as a function of the % tube wear (Figure 5). The tube material however is closer to the sensing coils than the AVBs. By taking advantage of the reduced skin-depth or penetration depth with higher frequencies compared to extended penetration depths for lower frequencies, higher frequencies can be used to quantify wear independent of the distance from the AVBs then this information can be used to calibrate and adjust the response to AVBs primarily relying on the lower frequencies. A family of curves was created and a computer routine was used to aid the analysts to determine the best AVB gap estimate on a production basis (Figure 6).

![Figure 5: MRPC Response to AVB in the presence of various %TW wear](image)

Independently from the AVB gap measurement challenges, the array and MRP technology has been instrumental to describe and characterize the nature of the tube wear. Automated computer displays have been created to capture the detailed tube analysis to show exactly how the wear is manifested with both transverse tube and axial tube cross sections (Figure 7). The wear can clearly be identified to be opposingly aligned as one would expect for tube to tube wear associated with excessive vibration and tube contact. Understanding the wear locations and patterns is essential to designing and implementing repair and mitigation processes.

![Figure 6: MRPC family of curves created to aid in AVB gap considering wear](image)
ULTRASONIC GAP MEASUREMENT

Both ET array and MRPC technology have good accuracy but they require precise calibration and can be sensitive to subtle changes in the metallurgy of the tube and the AVB. Ultrasound is relatively insensitive to such metallurgical influences. The ability of ultrasound to penetrate through the tube wall and through the water-filled secondary side of the tube to the AVB and then reflect back from the AVB surface (or adjacent tube surface) through the secondary side water, through the tube wall and ultimately be received by the UT probe was tested. Although there was clearly a signal, analyzing the raw signal reflection to determine the distance between the tube and AVB proved to be difficult or impossible. The natural ringing and noise from the tube was the same order of magnitude or greater than the reflected signal from the AVB. To overcome this problem, software was developed to average the local tube wall noise and subtract it from the signal at each circumferential location around the tube. This enabled even more precise measurement of the AVB gap (Figure 8). This patent pending approach works well as long as there is no tube wear. AREVA NDE Solutions personnel are working to adjust this approach to also work in the presence of wear.

Based on this method, a field deployable UT system was developed (Figure 9). The measurement sequence first requires the secondary side to be filled with water. The UT probe is deployed much like an eddy current probe using a robotic SG bowl-mounted manipulator to align a snorkel with the tube to be inspected. A probe-driver then inserts the UT probe into the tube to the elevation to be inspected. The annulus between the probes fore and aft water seals is filled with water then the probe is rotated and translated through the region of interest generating a helical scan of the AVB region. Inspection speeds are only a few mm/second making the overall production rate only a few tube/hour.

Advantages of the UT examination approach include:

- Low measurement error (<± 0.5mils, 0.013mm)
- Independent of specific tube metallurgical parameters simplifying calibration

Disadvantages for UT measurement include:

- Slow inspection speeds compared to all eddy current methods.
- Need to flood the secondary side of the SG at least to the elevation of the highest AVB gap to be tested.
- Water must also be supplied to the primary side of the tube. This is managed within the UT-360 probe delivery system.
- The current method does not work in the presence of wear. Work is ongoing to improve the technique to work in the presence of wear but this approach is not yet available.
FIELD EXPERIENCE

Since developing these techniques, they have been deployed to 3 sites and measurements have been made on several thousand AVBs. This is not an experimental method. Rather it is a fully qualified field hardened inspection method that can be readily deployed as an extension of traditional inspection technologies.

CONCLUSIONS

Conventional axial bobbin probes are not capable to quantify AVB gaps due to the inability to separate the influence of two AVBs on the signal response. Array probes are capable to quantify the AVB gaps with the threshold of $< 0.004''$ (0.01mm) and the resolution of $0.002''$ (0.05mm) with relatively short inspection times (15-35 tubes/hour with a single probe). RPC is capable to quantify the gap with the threshold of $0.002''$ (0.05mm) and the resolution of $0.001''$ (0.025mm) with or without the presence of wear with longer inspection times (4-10 tubes/hour with a single probe). UT is capable to quantify the gap with the threshold and resolution of $0.0005''$ (0.012mm) but with no wear and still longer inspection times (~1 tube/hour for 6 AVBs only). These approaches are fully qualified and have been deployed several times for inspection of thousands of AVBs.

REFERENCES

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