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Resonance Testing for Fault Detection of Steam Generator Heat Transfer Tubing Walls

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Resonance Testing for Fault Detection of Steam Generator Heat Transfer Tubing Walls

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Abstract

Steam Generator tubes are a vital part of every nuclear power plant. The need to identify potential flaws in a timely manner is paramount. This paper investigates the effectiveness of using sound frequency techniques in detecting tube flaws. Tubes of differing metal compositions were tested using a speaker and accelerometer data acquisition system. A simple receiver was designed and built in order to test the effectiveness of data acquisition in the field. Its design is discussed later in this paper. A U-Bend steam generator tube assembly model was constructed and used as a test apparatus. While the results were inconclusive upon visual inspection, there is potential that advanced data analysis techniques would yield viable conclusions for the prototype receiver design developed for this experiment. Recommendations were made for future work involving the receiver design for commercial deployment of the device and recognizing the need for more extensive data analysis techniques.
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I. Introduction

With wall thicknesses of only one-fifth of inch (0.5cm), the steam generator u-tubes of a nuclear reactor plant are the expected location of a primary to secondary system leak and require immediate detection to minimize contamination of the secondary plant and exposure to facility personnel. The tube walls are designed with a small thickness to allow optimal heat transfer from the reactor coolant to the steam generator water, which will be converted to work as it rotates the blades of a turbine.

Strict chemistry controls ensure plant conditions that lead to caustic or corrosive environments are minimized to reduce the probability of a tube wall fault developing into a leak. Primary plant pressure during normal operating conditions is much higher than that of the secondary system, therefore ensuring that any leak in the steam generator tubes will result in possibly contaminated reactor coolant entering the secondary system and not in the opposite direction. Since the secondary plant is outside the reactor compartment, this incident has a potential outcome of the spread of contamination and radiation exposure.¹

In an attempt to prevent a primary to secondary leak, periodic inspections are performed on the u-tubes to uncover any faults. These faults include pin holes, cracks, dents, or any other anomalies that change the uniformity and integrity of the pipe wall. The current industry standard is to perform an eddy current test.

I.1 Eddy Current Testing

Eddy current testing (ECT), also known as Foucault current testing, uses high frequency AC current in a primary coil to generate a magnetic field which in turn induces circular eddy currents in the material of interest. When an alternating current passes through a coil placed adjacent to an electrically conductive material, electrical currents (eddy currents) are induced in the material as demonstrated in Figure 1. The coil is excited by applying a low-amperage alternating current of 50 kHz – 1000 kHz.² The penetration of induced eddy currents is inversely proportional to square root of the AC frequency.³
Eddy Currents are induced in material being tested by an exterior magnetic field. The eddy currents, in turn, generate electromagnetic fields that oppose the primary coil field and thereby change its effective electrical impedance. The magnitude and phase of this parameter depend on probe-to-material distance, geometry of test piece, material conductivity, and presence of defects. Thus, conditions that affect the material characteristics such as defects present in the near surface region can be detected by a change in the coil impedance. These are displayed as Lissajous figures on the eddy current instrument screen or a computer monitor as seen in Figure 2.

ECT has some disadvantages such as it can be applied only on electrically conductive materials, and is sensitive only to surface and near surface discontinuities. Also, since various factors as previously described may affect eddy current signals, data interpretation requires highly trained personnel and impedes the timely processing of this data. Furthermore, eddy current requires the movement of a probe.
along the entire length of the pipe which could result in the probe becoming lodged or causing damage to
the pipe wall. An alternative method for fault detection considered by this project is resonance testing
through sound waves or mechanical vibrations.

I.2 Resonance Testing

Resonance testing, if designed properly, can be performed with minor intrusion and may prove to
be as accurate in detecting faults. Resonance testing is currently used in industry, but little consideration
has been given to its application in heat exchanger tubing fault detection. Resonance testing can be
performed at ultrasonic or acoustic frequencies. For the purpose of this experiment, acoustic frequencies
will be used due to the relatively lower cost and easier accessibility of related equipment. However, future
experimentation should consider ultrasonic testing should acoustic testing be deemed inadequate.

Acoustics deal with sound propagation and sound absorption. Sound waves propagate through the
medium being tested in the frequency range audible to humans, which is approximately 20 Hz to 16 kHz.
Structure-borne sound, or mechanical vibrations in a structure, and radiated vibrations in the surrounding
air (audible sound) carry information that can be read by a sensor and interpreted by an analyst. Nearly all
objects will vibrate when they are hit or excited or somehow disturbed. The frequency or frequencies at
which the objects tend to vibrate after excitation are called natural frequencies or resonances. As with
eddy current, the resonances depend uniquely on the object's material, geometry and condition.

II. Data Acquisition on Various Materials

The task of this experiment was to assess and provide a new technology for detection of faults in
steam generator tubing walls to reduce the adverse effects of primary to secondary leak in a nuclear plant.
Acoustic resonances were chosen over ultrasonic due to time restraints. To ensure the technology was
feasible, two speakers, shown in Figure 3 were used to perform a crude acoustic resonance test.
II. Data Collection and Analysis on Carbon Steel Pipes

Following receipt of a new speaker and accelerometer, the two were used in conjunction to analyze two carbon steel pipes roughly 1.5 feet (20.32 cm) in length. The data was acquired via the LabView computer program. Pipe design was photographically documented in Figure 4.
The first of the tubes was considered normal. The second tube had a three-inch cut at one end as shown in Figure 5

![Carbon steel pipe with manufactured flaw used for data collection of resonance testing.](image)

**Figure 5:** Carbon steel pipe with manufactured flaw used for data collection of resonance testing.

The data acquisition was performed at 150 Hz. These frequencies were chosen because resonant peaks were observed in the Fast Fourier Transform (FFT) of the speaker and accelerometer output. This can be seen in Figure 6 and Figure 7

![Graph of Carbon Steel Tube Normal 150 Hz](image)

**Figure 6:** Carbon Steel Tube Normal 150 Hz
Figure 7: Carbon Steel Slit 150 Hz

The blue line in each figure represents the speaker that was driving the system, while the red line represents the accelerometer. It was expected that a noticeable difference would be seen between FFT of the normal tube and the flawed tube. Analysis of the data indicated that the sensitivity of the accelerometer used was lower than desired. The peaks from the accelerometer and speaker should have been similar in amplitude. This low response from the accelerometer could have been attributed to several factors that required further testing to determine. During this experiment the accelerometer device was placed as close to the top of the tube on the outside, while the speaker was taped to the bottom of the tube. This geometry could have been responsible for the weak response of the sensor. The difference in peak values between Figure 6 and Figure 7 was hard to determine. It appeared that the inserted flaw did not have a noticeable change in the FFT at 150 Hz, assuming that both pipes were identical in properties with the exception of the slit.

The procedure was repeated at 250 Hz and the results are shown in Figure 8 and Figure 9. It can be seen that there is a slight difference between the normal pipe and the flawed pipe. A peak was seen at 250 Hz for both pipes; however, the accelerometer peaks did not appear to match the speaker peaks at any other frequency. This could possibly be attributed to the flaw in pipe, but would require further testing and analysis.
An additional analysis was performed to see the change in the 150 Hz peak amplitude of both responses over time. This was performed using the data for 150 Hz. Figure 10 below shows the fluctuation of the ratio in the normal pipe and the slit pipe.
II.2 Data Collection and Analysis on Stainless Steel Tubing

An accelerometer and a speaker were used to analyze roughly 6 feet (1.89 meters) of stainless steel tubing. The first of the tubes was considered normal and the second had a 3 inch cut at one end.

![Figure 11: Stainless Steel tubing used for resonance testing.](image-url)
The data acquisition was once again performed at 150Hz and 250Hz. The data was acquired via the LabView computer program. These frequencies were again chosen because of the resonant peaks observed in the FFT of the speaker and accelerometer as shown in Figure 12 and Figure 13.

**Figure 12: Stainless Steel normal at 150Hz**

**Figure 13: Stainless Steel slit at 150Hz**
In each of the figures the blue line represents the speaker and the red line represents the accelerometer.

At 150 Hz normal (Figure 12) the speaker and the accelerometer peaks should be similar based on the results observed for the other data collection runs with stainless steel. Unfortunately this is not the case. This might be due to a faulty setup with the accelerometer being that the accelerometer was again placed too close to the top of the tube on the outside. However unexpectedly in Figure 13, the speaker
and accelerometer are in unison until the peak at a frequency at 750 Hz. The process was again repeated at 250 Hz as shown in Figure 14 and Figure 15. Unfortunately, the results proved to be the same as for the tests done for the normal tube at 150 Hz. Once again, the accelerometer was most likely placed in an incorrect position when collecting data.

II.3 Data Collection and Analysis on Inconel Pipe

An accelerometer and a small speaker were used to analyze the 6 feet (1.89 meters) of undamaged Inconel piping. This piping closely resembles that of steam generator tubes used in a nuclear power plant. The data acquisition was performed at 150 Hz and 250 Hz because these frequencies showed the most prominent peaks in the FFT graph. The data was acquired via the LabView computer program. The blue line, in both Figure 16 and Figure 17, represents the speaker and the red line represents the accelerometer.

![INC at 150 Hz](image)

*Figure 16: Inconel without flaws at 150Hz*
Figure 16 shows that the resonance of the speaker and amplitude complement each other confirming that the accelerometer is working correctly even though the accelerometer was installed on the outside of the tube. Unfortunately, when the frequency was increased to 250 Hz as seen in Figure 17, the accelerometer did not show a correlation to the speaker.

**III. Sensor and Exciter Plate Design**

Attempted collection of data was performed with the accelerometer resting inside the pipe, but no data was received by the instrumentation. The problem was determined to be one of two issues. Either the inconsistent geometries of the flat accelerometer surface and curved surface of the pipe walls did not allow for proper contact, or the accelerometer lacked an applied force against the wall to allow proper transmission of vibrations to the accelerometer.

This research indicated that a couplant might be necessary to ensure proper contact and transmission of vibrations. A probe was designed with air as the couplant for ease of manufacturing with the time constraints in place. Hydrostatic inflation of the same probe would increase sensitivity, but would require future experimentation.
Excitation of tubes was relatively easy and performed by different means. For this reason, emphasis was placed on design of a sensor plate.

A model of four steam generator tubes was constructed as seen in Figure 18.

III.1 Exciter Plate Design

Initially, one sensor probe was tested individually with a speaker attached to the outside of the tubing as shown in Figure 19.
Later testing was accomplished by the use of a borrowed design in which vibrations were transferred from a speaker to a plate. The plate had rods inserted into it with a metallic ball on the end of each rod. Figure 20 is a photograph of the manufactured device.

The design used was adequate for excitation of the tubing, but no inspections were performed to determine the possibility of damage to the tube walls from the metallic balls.

### III.2 Sensor Plate Designs

To ensure proper transmission of vibrations from tube walls to the sensor without adding stiffness that would interfere with data acquisition, an Inflatable Plug Sensor Probe (IPSP) was designed and used. The initial design consisted of an individual probe with an accelerometer on the end. Based on the principal that industrial settings normally consist of high audible levels, accelerometers were chosen over microphones to eliminate background noise affecting data acquisition. A design schematic can be seen in...
Figure 21 and the actual manufactured probe can be seen in Figure 22. Ideally a commercially available sensor plate would consist of several probes of the type seen in Figure 21.

Figure 21: Sensor Probe Design

Figure 22: Sensor Probe in Use
The probe was designed to be inflated maximizing its contact with the tube wall by use of air as a couplant and applying force to the walls. Argon was used as shown in Figure 23 due to safety considerations because it is an inert gas.

![Figure 23: Initial Set-up of Inflatable Plug Sensor Probe](image)

The accelerometer was attached to the center of the tip of the probe to avoid contact with the wall. This ideally would ensure resonance would transmit from wall to plug to accelerometer.

Data collection was successful, therefore, designing was continued to create a sensor plate using the same technology. Figure 24 shows the final manufactured IPSPs installed on the sensor plate. During testing one probe did fail due to the use of low grade materials as shown in Figure 25.

![Figure 24: Inflatable Plug Sensor Probe Installed on Sensor Plate](image)
Figure 25: Failed Inflatable Plug Sensor Probe

Time constraints greatly affected the sensor plate design used. Figure 26 shows the remedial air supply tubing design while Figure 27 shows the wire from the accelerometer had to be run along the plug instead of interior.

Figure 26: Air Supply Tubing to the Sensor Plate

Figure 27: Accelerometer Wire Exposed to Design Time Constraints
The prototype design used a simple balloon/accelerometer pairing system. In order for testing to be carried out in the field, the device would have to be constructed in a sturdier manner. The prototype was constructed using common plumbing supplies and children's balloons to demonstrate proof of the principle. The actual device would have to be made of lightweight and sturdy materials. Latex or rubber material would have to be used for the balloon or plug part of the tube inserts. The base of the apparatus could be made of a durable plastic so that it is lightweight. The design of the apparatus should be altered such that the accelerometer can be mounted at the top of the tube insert with the cord running internally through the tube insert. This is to insure that only the balloon or bladder would be making contact with the inner tube wall.

As previously mentioned, hydrostatic inflation of probe plug is expected to be a more efficient than pneumatic inflation. Furthermore, use of solenoid valves and pressure relief devices could be used to design an automated system. An apparatus could be designed large enough to test a much larger amount of tubes at once. This would limit the man-hours required for removal and installation. Figure 28 is a system diagram of an automated test rig design.

Figure 28: Automated Sensor System Design Schematic
IV. Acoustic Resonance Testing of Steam Generator U-tube Model

Our whole receiver apparatus was used in collecting data on the steam generator model. This was done in union with the driver pictured in Figure 20. The data was acquired via the LabView computer program. This was done with an undamaged pipe and a pipe with a slit in it. Both were done with a driven at 200 Hz, which is the frequency that produced the most prominent peaks in the observed FFT graph created by LabView.

Figure 29 below shows the FFT response for an undamaged steam generator tube driven at a frequency of 200 Hz.

![Steam Generator Tubing Without Flaw at 200Hz](image)

**Figure 29: Steam Generator Tubing Without Flaw at 200Hz**

The speaker peak is naturally more pronounced because it is the input taken directly from the waveform generator/amplifier. The accelerometer peak is located at the same frequency as that of the speaker, 198.1935 Hz. This variation from the selected 200 Hz is most likely due to error in the connection between the waveform generator and the amplifier. Other peaks at 400 Hz, 600 Hz, 800 Hz, etc. can be seen. This is more noticeable in the accelerometer output since these frequencies are received quite similarly by the accelerometer, whereas the input to the speaker is specifically at 200 Hz.

Figure 30 below shows the FFT response for a steam generator tube damaged with a slit and driven at a frequency of 200 Hz. The peaks at 200 Hz, 400 Hz, etc. can be seen as in the response from the undamaged tube.
The input frequency was 200 Hz, and thus harmonics at $N \times \text{Order}$ were expected to be 200 Hz, 400 Hz, 600 Hz, 800 Hz, and so on. While non-synchronous peaks, those at $.5N \times \text{Order}$, were seen for both the normal and flawed steam generator models, the peak amplitudes were greater for the flawed steam generator model. This shows promise for future testing and application of the receiver design, as non-synchronous harmonics generally provide insight into flaws for many different types of machinery. It is important to note that this result was reproducible over many tests of the steam generator model.

Figure 31 below is used to distinguish the difference between the main peaks in Figure 29 and Figure 30.
A ratio of the accelerometer peak to speaker peak is done since the input amplitude was slightly different for the two tests. The peaks are both steady over time, but the peaks for the slit tubing were higher than those of the normal tubing. This is separate from the ratio observed in Figure 10 because a different system was used in acquiring the data for the steam generator.

V. Conclusion

Collected data indicates that resonance testing of steam generator u-tube walls for the purpose of flaw detection is possible and could prove to have advantages to current industry methods, in that data analysis of non-synchronous harmonics could possibly be used to determine number and size of faults in the tubing. Furthermore, the receiver prototype even with its simplicity in design and economical materials provided consistent data over multiple test runs of the steam generator model as shown in the steady ratios of Figure 31.

VI. Future Work

More work should be done in the analysis of the data gathered from the device. More extensive data analysis techniques should be deployed so that a difference in tubes can be determined from the data. Techniques such as Singular Value Decomposition and F-distribution should be deployed in conjunction with the Fast Fourier Transform data that has been gathered. Our design should be expanded to more commercial steam generator designs that currently use other technologies to detect flaws. These techniques should help to shed light on the subtle variations between normal and flawed tubes.
References


