Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Diagnosis of Steam Generator Tubing Degradation Using Fuzzy Logic and Wavelet Transform Methods

Key Yong Sung[1], Belle R. Upadhyaya[2] and Wesley C. Hooper[2]

1) Korea Institute of Nuclear Safety, Korea
2) The University of Tennessee, USA

ABSTRACT : Eddy Current Testing (ECT) is the predominant inspection procedure for monitoring steam generator (SG) tubing integrity. This study is to develop an automated diagnostic system using ECT data for the identification and sizing of SG tubing degradation by fuzzy logic, and damage mechanism classification by wavelet transform techniques. Fuzzy logic system can provide fast flaw detection and size estimation within reasonable accuracy of about 90%. Preliminary results indicate that wavelet analysis can be a promising tool for damage mechanism classification of ECT signals.

1. INTRODUCTION

The integrity of steam generator (SG) tubing in nuclear power plants has to be maintained in order to maximize the plant thermal efficiency and to protect the release of radioactive materials to the environment. Eddy current testing(ECT) is the predominant testing procedure for monitoring SG tubing integrity. ECT is based on the principle of electromagnetic induction between a test coil and a steam generator tube. As the test coil is moved through the steam generator tube, the alternating magnetic field, which is produced by alternating currents, penetrates the tube material and generates continuous, circular eddy currents which flow circumferentially around the tube. The induced eddy currents produce an opposing secondary magnetic field which has a weakening effect on the primary magnetic field. Degradation in the steam generator tube wall obstructs the eddy current flow, lengthens the eddy current path, reduces the secondary magnetic field, and increases the coil impedance.

Two types of eddy current probes are commonly used: bobbin probe and rotating pancake probe. The bobbin probe is the most frequently used one in steam generator tubing inspection because of a relatively fast inspection speed with reasonable accuracy. It is usually used for detecting volumetric damage mechanisms in which the major axis of the discontinuity is oriented perpendicular to the direction of eddy current flow. These damage mechanisms include thinning, pitting, wear, and axial stress corrosion cracking. However, the bobbin coil is not effective in the detection of certain damage forms that occur circumferentially over the tube wall. The eddy current test using the pancake probe has a slow inspection speed. Therefore, this probe is usually used for confirming bobbin coil indications, detecting circumferential cracking, and examining regions of the tube where the bobbin coil cannot work effectively [1,2].

Due to the complexity of the analysis, poor signal-to-noise ratio, and the need to process a large amount of data, ECT analysis needs highly qualified personnel and relies heavily on evaluator's ability. Particularly, eddy current inspection systems are sensitive to many variables than just tube degradation. The ability to distinguish between actual tube flaws and artifacts due to other variations near the eddy current coil require the attention of highly trained and experienced data analysts.

The purpose of this study is to develop an automated diagnostic technique using bobbin ECT data for the identification and sizing of SG tubing degradation by fuzzy logic and damage mechanism classification by wavelet transform technique. The eddy current test data are selected from over 300 tube data provided by the Electric Power Research Institute [3].

2. DEVELOPMENT OF THE ECT DATA ANALYSIS SYSTEM

The general approach for an automated SG eddy current data analysis system is shown in Figure 1. This approach integrates data calibration, noise compensation, flaw identification and sizing, and damage mechanism classification, which is still being studied. This system has been developed using MATLAB software and Toolboxes.

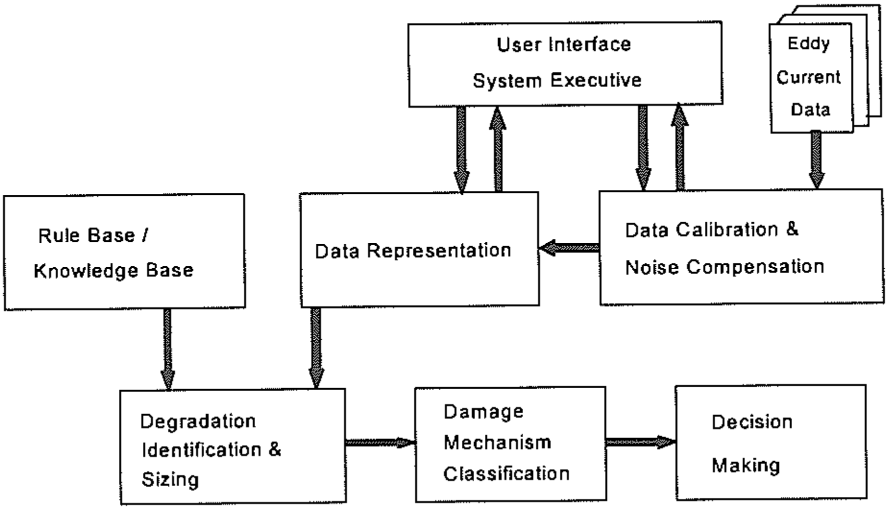

Fig.1 Schematic of the diagnostics system for eddy current test data analysis.

3. NOISE COMPENSATION AND DATA CALIBRATION

The discrete wavelet transform (DWT) is used for de-noising and filtering unwanted frequency components from the raw eddy current signals. DWT can separate an eddy current signal into several separate frequency ranges. For the removal of higher frequency noises de-noising technique is adopted and any component of the signal which does not exceed the threshold limit is removed. The low frequency component of signal like drift is also removed by DWT filtering function [4,5]. Figure 2 shows the real part of a typical ECT signal. Figure 3 shows the same signal after denoising the high frequency noises and filtering the low frequency drift. The de-noised, filtered signal is much "cleaner" looking and more easily recognized as possible tube wall degradation than is the raw signal

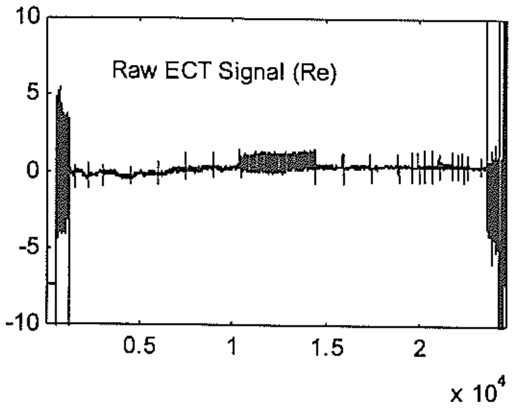

Fig.2 A typical EC signal

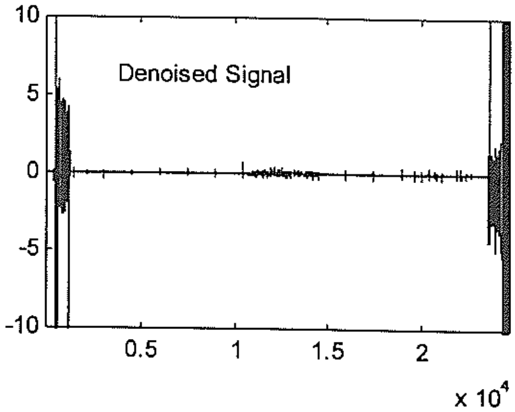

Fig.3 EC signal after removing the low and high frequency components

In a typical EC test by bobbin coils, the size of degradation is determined by the phase angle and the amplitude of the impedance plane trajectory. ECT data are acquired using various excitation frequencies since the eddy currents corresponding to different frequencies penetrate the tube wall differently. To measure the correct size of the discontinuities, calibration procedure has to be performed before data analysis. Calibration for phase angle is typically accomplished with ASME Standard Calibration tubes. These tubes should be identical in material and size to the tubes to be tested. The calibration tube has notches drilled to 100%, 80%, 60%, 40%, and 20% through the tube wall (TW). Phase angle calibration is performed by rotating the signal from the 100% TW hole to 40 degrees in the clockwise direction from the negative x-axis. Amplitude calibration is generally performed by setting the maximum amplitude of impedance from the 20% TW hole to a value of 2 volts. The same procedure is performed for each data channel. In addition, calibrated phase angles (100%, 80%, 60%, 40%, 20%) for each eddy current channel have to be recorded for use as the center of membership functions in the fuzzy logic algorithm to estimate the defect size [4,6].

Mechanical wear, such as Anti-Vibration Bar (AVB) fretting, needs another calibration process which is performed using only the maximum amplitude of impedance from artificial defects, not phase angles, using the AVB wear standard tube.

4. IDENTIFICATION AND SIZING OF TUBE WALL DEGRADATION

This system uses fuzzy logic in order to locate and size tube wall degradation in steam generator tubes. Fuzzy logic is the logic of "approximate measurements" and is somewhat similar to the human decision making process. The important difference between the fuzzy logic approach and the traditional approaches is that the former uses qualitative information whereas the latter requires rigid mathematical relationships describing the process. In classical logic an element x of the set X belongs to a set A or does not belong to A. On the other hand, in fuzzy set theory, an element has a degree of membership in a given set from 0 (completely not in the set) to 1 (completely in the set). This property allows fuzzy logic to solve problems with uncertain situations and imprecise information [6].

This fuzzy system consists of three inputs and two outputs. As the system input, the three phase angles for each of the three highest differential channels at one point are used. The system output is the estimated depth of the degradation and the decision whether or not tube

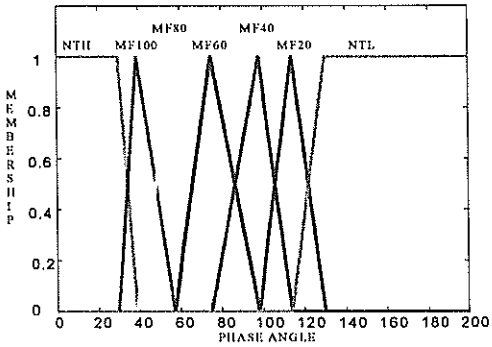

Fig.4 Input Membership Functions

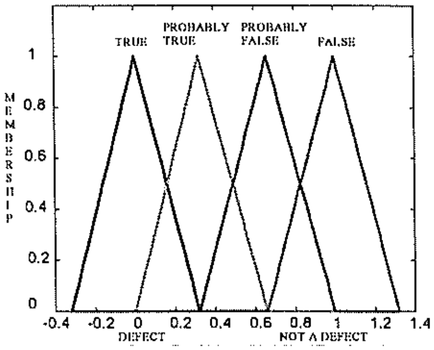

Fig.5 Output1 Membership Functions.

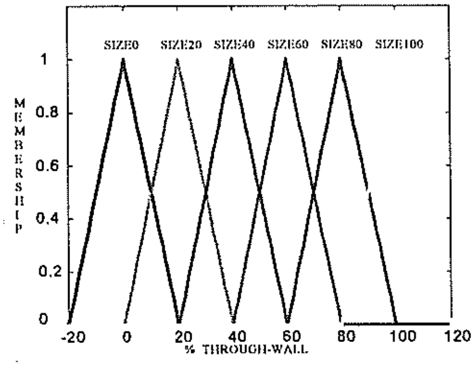

Fig.6 Output2 Membership Functions.

wall degradation has occurred at the point being observed. The system first calculates the phase angle between all successive points of total signals for each channel. If the calculated angles show the correct rotation corresponding to tube wall degradation, then that point is flagged as a possible tube wall degradation. The depth of degradation is determined by applying the corresponding angles of the three channels to the fuzzy logic routines. Three of the highest frequency channels have their own input membership functions and one of them is shown in Figure 4. The input phase angles for each channel are fuzzified by determining their membership into seven fuzzy sets: MF100, MF80, MF60, MF40, MF20, not a defect on the high side (NTH), and not a defect on the low side (NTL). The range of the inputs is from 0 to 360 degrees. The membership functions for the first five sets are triangular. The centers and spreads are determined by using the calibration data for each channel. MF100 is centered on the phase angle (about 40 degrees) for a 100 percent through-wall defect. MF80 is centered on the phase angle for 80 percent though-wall defect. NTH and NTL are trapezoidal functions covering the remaining input space. The system output consists of two parameters, one for the confidence of the estimation (Output1) and the other for depth determination (Output2). Their membership functions are shown in Figure 5 and 6, respectively. Output1 has four fuzzy sets: True, Probably True, Probably False, and False. The range of the output is from 0 to 1. An output of less than 0.5 represents a defect being present. Output 2 crisply estimates the depth of the degradation as a percent of through wall.

Table 1. Fuzzy Logic Rule Base

Rule #	Fuzzy Logic Decision Rules
1	If ch1 is NTH then output1 is FALSE and output2 is SIZE100
2	If ch2 is NTH then output1 is FALSE and output2 is SIZE100
3	If ch3 is NTH then output1 is FALSE and output2 is SIZE100
4	If ch1 is MF100 and ch2 is MF100 and ch3 is MF100 then output1 is TRUE and output2 is SIZE100
5	If ch1 is MF100 and ch2 is MF100 and ch3 is MF80 then output1 is TRUE and output2 is SIZE100
6	If ch1 is MF100 and ch2 is MF100 and ch3 is MF60 then output1 is PROBABLY TRUE and ouput2 is SIZE100
7	If ch1 is MF100 and ch2 is MF100 and ch3 is MF40 then output1 is PROBABLY FALSE and output2 is SIZE100
8	If ch1 is MF100 and ch2 is MF100 and ch3 is MF20 then output1 is FALSE and output2 is SIZE80
9	If ch1 is MF100 and ch2 is MF80 and ch3 is MF100 then output1 is PROBABLY TRUE and output2 is SIZE100
10	If ch1 is MF100 and ch2 is MF80 and ch3 is MF80 then output1 is PROBABLY TRUE and output2 is SIZE80
11	If ch1 is MF100 and ch2 is MF80 and ch3 is MF60 then output1 is PROBABLY FALSE and output2 is SIZE80
12	If ch1 is HMF100 and ch2 is MF80 and ch3 is MF40 then output1 is FALSE and output2 is SIZE80
13	If ch1 is MF100 and ch2 is MF80 and ch3 is MF20 then output1 is FALSE and output2 is SIZE80

The rules inside a fuzzy system represent the relationships between system inputs and system outputs. After the inputs are fuzzified, the rule base is applied. The rule base consists of 107 rules. Table 1 shows some of the rules used. The Mamdani "min" implication operator is used to determine the strength of each rule used. After rule evaluation, more than one rule may be fired through the aggregation process which is a means of combining the output membership functions. In this study, "sum" aggregation method is used. It means that the output membership functions are added together. A defuzzification procedure is used to obtain a crisp output from the aggregated fuzzy set. This is done by finding the "centroid" of the aggregated fuzzy output membership functions.

Many locations in the eddy current data show proper phase rotation but are of such a small voltage magnitude that it is very unlikely that tube wall degradation is actually present. Therefore a voltage threshold has also been added to the fuzzy logic flaw detection routine in order to reduce the number of false calls made by the system. The voltage threshold is set at 0.10 volts for each channel. An indication given by the fuzzy system must exceed this threshold to be flagged as a possible defect.

If it is known that there are AVB defects in tubes, this system is also able to calculate the accurate degraded size of fretting by using AVB fuzzy logic rule based on the AVB calibrated data. AVB fuzzy system has almost similar structure with previously described one except the calibration data. In this case AVB calibrated data can be more easily obtained than in phase angle calibration process, using a simple procedure to find the maximum amplitude at simulated defect area of AVB calibration tube.

The fuzzy logic flaw detection system was tested on the eddy current data taken from EPRI performance demonstration database (PDD) [3]. The kinds of defect considered in this study were limited to four mechanisms as shown in Table 2. The database consists of 84 tube wall degradations in 40 tubes, and defect size greater than 20% are considered here. Their defect sizes and locations were already described in the PDD from the original field analysis of the indications as well as the results of metallurgical tests taken after the tubes were pulled.

Table 2. Results of the fuzzy logic flaw detection system

Defect mechanism	Number of tubes	Number of defects	Number of defects confirmed by fuzzy system
SCC	16	34	27 (79 %)
IGA/SCC	3	3	3 (100 %)
IGA	2	10	4 (40 %)
Pitting	14	19	17 (89 %)
AVB	5	18	18 (100%)
Total	40	84	69 (82 %)

Table 2 shows the number of tubes and indications reported in the database and the number of detected indications by fuzzy system for each mechanism. As indicated in Table 2 the system has comparatively good capability for flaw detection and size estimation for SCC, Pitting, and AVB degradation. However, it has difficulty with IGA data. Inter-granular attack (IGA) is a term used to describe a morphology characterized by uniform or relatively uniform attack of grain boundary over the surface of the tubing. It usually occurs over a relatively large extent but relatively shallow depth exhibiting three-dimensional features. Actually, the most IGA defects described in the database were not called by initial eddy current analysis, but later determined by re-analysis and metallurgical investigation. The percentage of detected indications called by the fuzzy system increased from 82% to 88% after ruling out IGA data set. It should also be noted that the system had relatively small false calls and located a large number of additional indications which had not been previously called at all. These additional indications are from external structures like tube support plates and noises representing small defects ranging from 10 to 20 percent through-wall. Even though we encountered some problems, it was found that this system can provide a fast analysis tool for eddy current signals within reasonable accuracy in flaw detection. Usage of mixed channel, well-adjusted de-noising variables, and proper amplitude threshold can more effectively reduce the spurious callings and improve the accuracy of flaw detection.

5. CLASSIFICATION OF DAMAGE MECHANISMS

It is believed that eddy current signals from tube wall degradation caused by different damage mechanisms may exhibit different characteristics in the frequency domain and that these characteristics may be identified and used to classify the damage mechanisms. The classical Fourier transform is often used to estimate the energy in the stationary signal at different frequencies. However, this method is not suitable for transient or non-stationary signals since the time information is lost in transforming to the frequency domain. The wavelet transform (WT) is a means of transforming a non-stationary signal to the frequency domain while retaining much of the time-related information. Hence WT is supposed to be a useful tool to characterize the eddy current defect signals since they always show transient signals in the neighborhood of a defect.

Particularly, this study adopts discrete wavelet transform(DWT) method which uses scales and positions based on a power of two, so called dyadic scales and positions. The output of DWT consists of two components, approximations and details, generated by the decomposition process. The approximations are the high-scale, low-frequency components (low-pass) of a signal. The details are the low-scale, high-frequency (high-pass) components of a signal. The original signal passes through two complementary filters and emerges as two decomposed signals. The decomposition process can be iterated with successive approximations, so that one signal is broken down into many lower-resolution components.

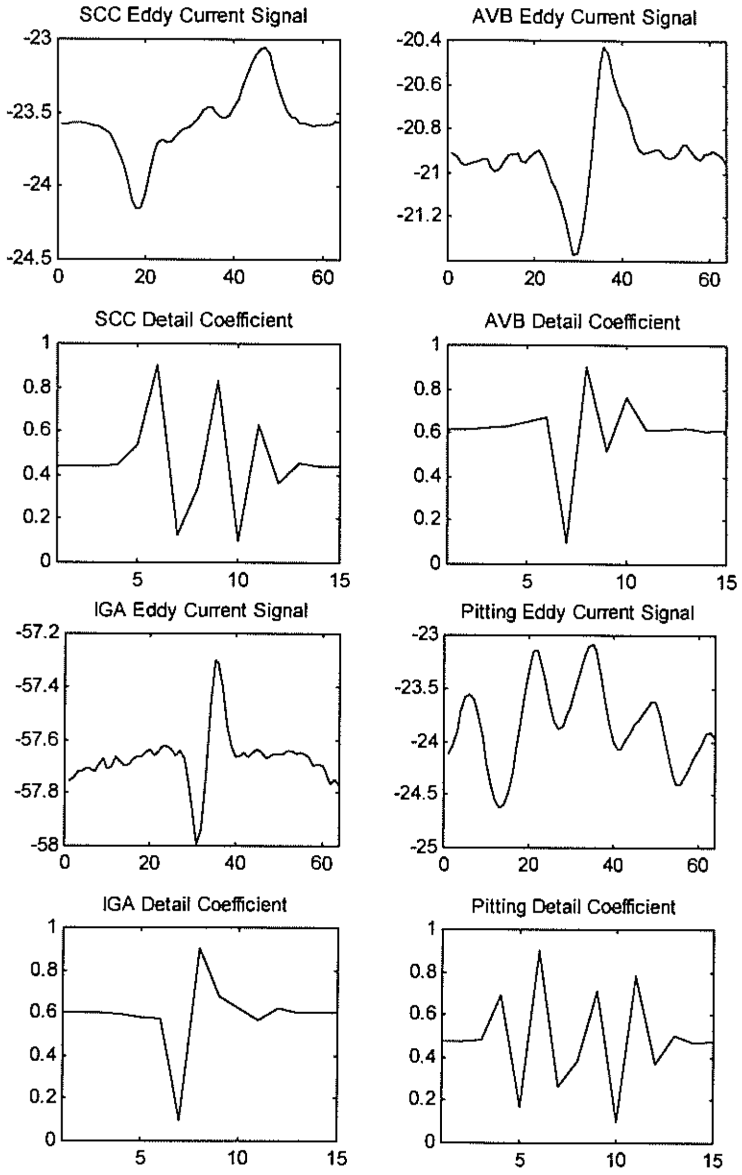

Fig. 7 Discrete wavelet transform representations of eddy current signals for four damage mechanisms.

Each decomposition process generates the coefficients of the corresponding approximation and detail [5].

In this study DWT coefficients generated from four kinds of eddy current signals with different mechanisms such as inter-granular attack (IGA), stress corrosion cracking (SCC), pitting, and AVB fretting are investigated. Figure 7 shows the original eddy current signals of four tube wall defects and their scaled second-level coefficients formed by Daubechies wavelet function (db 5), respectively. In each case, the location of the degradation is centered on data point number 32 of the EC signal. The figures show that detail coefficients are drastically changed and very sensitive at the points of discontinuity of original EC signals. It is also found that detail coefficients simply represent the characteristics of original signals with a clear classification factor like the number of peaks or the pattern of coefficients. These characteristics are consistent over the entire existing database. With proper pattern recognition method, the classification may be accomplished in an easy and simple manner. However, it should be noted that a much larger database should be examined before these results can be verified with a high degree of certainty. It is possible that these characteristics are due to coincidental similarities, which are not representative of all cases (that is, certain noise patterns, relation to support plates, etc.).

6. CONCLUSIONS

A system is being developed to automate the analysis system of eddy current test data by using fuzzy logic and wavelet transform. This fuzzy system is effective in locating and estimating the size of SCC, pitting, and AVB tube wall degradation in ECT data taken from operating nuclear plant steam generators. The success rate of detection is about 90% except for the IGA defect. This system also produced a few false calls originated from noise and external structures. Usage of mixed channel, well-adjusted de-noising variables, and proper amplitude threshold can more effectively reduce the spurious callings and improve accuracy of flaw detection. It is also found that detail coefficients calculated from discrete wavelet transforms can represent the characteristics of defects with a clear classifying factor like the number of peaks or the pattern of coefficients. Preliminary results indicate that wavelet analysis can be a promising tool for damage mechanism classification of ECT signals.

REFERENCES

1. Nondestructive Testing Handbook: Vol.4 – Electromagnetic Testing, American Society for Nondestructive Testing, 1989
2. Mix, P.E., Introduction to Nondestructive Testing, John Wiley , New York, 1987
3. Brown, S., et al., "Steam Generator Eddy Current Data Analysis Performance Demonstration Review Material." EPRI NDE center, October 1995.
4. Hooper, W.C. and Upadhyaya, B.R., An Automated Diagnostics System for Eddy Current Data Analysis of Steam Generator Tubing, Research Report, EPRI/UTNE/93-17, June 1998
5. Misiti, M., et al., MATLAB Wavelet Toolbox User's Guide, The Math Works, 1996
6. Tsoukalas, L.H. and Uhrig, R.E., Fuzzy and Neural Approaches in Engineering, John Wiley and Sons, 1997