FOURIER DESCRIPTOR CLASSIFICATION OF MAGNETITE BUILDUP
IN PWR STEAM GENERATORS

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INTRODUCTION

Emphasis on the reliability and safety of nuclear power plants has contributed to a growing interest in the development of rigorous preventive maintenance schemes. A major part of the effort has been directed at methods of inspecting steam generators in as much as they serve as a crucial link in the transfer of power from the nuclear reactor to the steam turbine. Steam generators typically consist of Inconel tubes anchored at intervals with carbon steel support plates as shown in figure 1. The primary coolant from the nuclear reactor circulates through these tubes. Heat is transferred to the secondary coolant by conduction through the tube wall generating steam which is used for running the turbine.

Fig. 1. Nuclear power plant steam generator.
Exposure to the mixture of water and steam causes corrosion of the support plates resulting in the growth of magnetite in the interstices between the support plate and the tube. The growth, unless checked, can dent and eventually crack the tube leading to a hazardous situation caused by contamination of the secondary coolant. A solution to the problem lies in periodically flushing the magnetite out of the crevice gap using appropriate chemical reagents. Information regarding the amount of magnetite present in the crevice gap is therefore crucial to utilities in order to initiate flushing procedures. An additional need for characterizing the magnetite present in the crevice gap develops during the flushing procedure to monitor the process and determine when and if the operation should be terminated.

One of the methods for characterizing the amount of magnetite present involves the use of a variable reluctance (VR) probe [1]. The VR probe consists of a coil wound over a mild steel bobbin with as many as eight Hall elements mounted on the periphery of the bobbin. The magnetomotive force generated by the coil excited by a d.c. excitation source drives magnetic flux around a path which includes the crevice gap and the support plate when the bobbin is aligned with the plate. The flux density measured by the Hall element is a function of the reluctance of the path and hence the condition of the crevice gap. Figures 2 and 3 show plots of the flux path for two different positions of the bobbin with respect to the support plate. A typical amplified Hall element signal is shown in figure 4. The probe is initially calibrated using a rig consisting of accurately machined crevice gaps of known dimensions to obtain a relationship between the peak magnitude of the probe signal and the gap width. The presence of magnetite is detected by examining the frequency spectrum of the signal.

Fig. 2. Flux path when the variable reluctance probe is aligned with a support plate.

Fig. 3. Flux path when the variable reluctance probe is away from a support plate.

Fig. 4. Typical variable reluctance probe signal.
An alternative method is to use a conventional differential eddy current probe for detecting the presence of magnetite. This method has a major advantage in that archival records of eddy current signals are usually available for purposes of comparison and evaluation. The differential eddy current probe consists of two coils connected in the differential mode excited by an alternating current source. When the probe moves past a defect, changes in the differential impedance trace a trajectory that is characteristic of the nature of the defect. Similarly when the probe is moved through the support plate region in the tube, the differential impedance traces a complex trajectory reflecting the presence of the carbon steel support plate, the magnetite present in the crevice gap and the presence of any defects or inhomogeneities if present. Figure 5 shows a typical impedance plane trajectory. The primary objective is to design a characterization scheme which allows determination of the amount and disposition of magnetite in the crevice gap and the presence of any defect in the region by examining the impedance plane trajectory. This paper describes the use of the Fourier descriptor method for achieving this purpose.

![Fig. 5: Typical impedance plane trajectories.](image)

![Fig. 6. A simply closed curve.](image)

**FOURIER DESCRIPTORS**

Although the use of Fourier descriptors for the representation and classification of impedance plane trajectories has been described elsewhere [2, 3], a brief review of the method follows for the purposes of maintaining continuity. Consider a simply closed curve as shown in figure 6 whose complex contour function \( U(\ell) \) is defined as

\[
U(\ell) = x(\ell) + jy(\ell)
\]

where \( \ell \) represents the arc length measured from any arbitrary starting point \( P_0 \), \( x \) and \( y \) represent the real and imaginary components of the trajectory and \( j \) is the imaginary number \( \sqrt{-1} \). If the total arc length of the curve is \( L \) then

\[
U(\ell + L) = U(\ell)
\]
Consequently the complex function \( U(\ell) \) is periodic with period \( L \) and can therefore be expanded in a Fourier Series, i.e.

\[
U(\ell) = \sum_{n=-\infty}^{\infty} C_n \exp\left(\frac{\text{j}2\pi n L}{L}\right)
\]

where

\[
C_n = \frac{1}{L} \int_{0}^{L} U(\ell) \exp\left(\frac{-\text{j}2\pi n \ell}{L}\right) d\ell
\]

Since the curves under consideration are very smooth, the coefficients \( C_n \) decay very rapidly in magnitude as \( n \) increases. Equation (3) can therefore be approximated by a finite series

\[
U(\ell) = \sum_{n=-M}^{M} C_n \exp\left(\frac{\text{j}2\pi n \ell}{L}\right)
\]

In order to obtain shape descriptors which remain unaffected by the choice of starting point and slow drifts in the eddy current instrument settings, functions of coefficients which are invariant under rotation, translation and scaling of the curve are determined. An example of such a descriptor is given by

\[
b_n = \frac{C_{1+n} C_{-n}}{C_1^2}, \quad n \neq 1
\]

These descriptors are incorporated into a feature vector for classification purposes.

Several methods for classifying the feature vectors and hence the defect signals exist. These include Bayesian Classifiers and clustering algorithms [4]. However the method described in this paper is different in that a numerical model is used to generate prototypes or specimen signatures for use in the classification algorithm. Classification is accomplished by determining the closest prototype in the feature space.

FINITE ELEMENT MODEL

Feature vector prototypes are generated by computing the Fourier descriptors of impedance plane trajectories obtained by using a finite element model for a variety of magnetite buildup profiles with and without tube defects. The finite element method is a numerical method for solving the governing equation describing the eddy current phenomena which fall within the quasistatic domain of the electromagnetic spectrum [5, 6]. The governing equation, which can be derived [7] in terms of the vector magnetic potential \( \bar{A} \) neglecting the displacement current is given by

\[
\nabla \times (\nabla \times \bar{A}) = -\bar{J} + j\omega \bar{A}
\]

where \( \nabla \) represents the reluctivity, \( J \) and \( j\omega \bar{A} \) represent the impressed \( \bar{A} \) and induced eddy current density respectively. If the geometry under consideration is axisymmetric, equation (7) reduces to

\[
\nabla \left( \frac{\partial^2 \bar{A}}{\partial r^2} + \frac{1}{r} \frac{\partial \bar{A}}{\partial r} + \frac{\partial^2 \bar{A}}{\partial z^2} - \frac{\bar{A}}{r^2} \right) = j\omega \bar{A} - \bar{J}
\]
A direct analytical solution to the governing equation is generally not feasible except for the simplest of defect geometries. Consequently numerical methods have to be used. The finite element method involves discretization of the physical domain of interest by a mesh consisting of triangular elements. Instead of solving the governing equation directly, it is incorporated into an energy functional which is minimized at each of the nodes with respect to \( \mathbf{A} \). Minimization of the functional leads to a matrix equation which when solved leads to the solution. The solution takes the form of vector magnetic potentials defined for each node in the mesh which satisfy the governing equation. Among other derived quantities, the complex impedance of the differential coils can be approximated from the nodal point values of \( \mathbf{A} \). For determining the impedance plane trajectory corresponding to a specific defect, the probe is positioned initially at a location far away from the defect in the finite element mesh. It is then progressively stepped closer to the defect and at each step the differential impedance of the coil arrangement is computed.

NEAREST NEIGHBOR METHOD

In order to quantify the amount of magnetite present, a variety of crevice gap conditions are simulated using the finite element model and the corresponding impedance plane trajectories obtained. The Fourier descriptor feature vectors are then computed and treated as prototypes in the feature space. The given impedance plane trajectory is then classified by finding the nearest prototype using the Euclidean norm in the feature space.

RESULTS

In order to assess the performance of the approach, the method was used to classify eddy current signals obtained from a model boiler at Combustion Engineering, Connecticut. The experiment was unique in that it was conceived as an opportunity to test and study the efficacy of the chemical flushing operation. This not only allowed pre and post flushing inspection of the boiler but also inspection during the intermediate stages. Figure 7 shows progressive changes observed in the eddy current impedance plane trajectories during the test on a tube. The objective was to ascertain if the method described earlier could be used for characterizing the amount of magnetite present in the crevice gap. The prototype feature vectors were obtained by using the finite element method to generate the impedance plane trajectories whose descriptors were then computed. Finite element simulations included axial and radial buildup of magnetite with and without denting of the tube. In addition situations involving partial flushing of magnetite were also simulated. A total of 36 prototype feature vectors were obtained from finite element simulations. Figures 8, 9 and 10 show typical trajectories obtained. The signals from the model boiler were initially recorded on site with an analog tape recorder. The signals were subsequently read, digitized and transferred to a computer for analysis and classification. Classification was accomplished by computing the Fourier descriptor feature vector and identifying the nearest prototype generated by using the finite element method. Since the prototype is related to a specific magnetite-buildup/defect profile, the condition of the crevice gap in the boiler can be estimated. Figure 11 shows a typical classification result.
Differential eddy current probe signals

Tube number 9A 50 kHz
Cold Leg

Fig. 7. Eddy current impedance plane trajectories obtained from the model boiler with tests carried out at periodic intervals.
Fig. 8. Impedance plane trajectories predicted by FEM for radial buildup of magnetite.

Fig. 9. Impedance plane trajectories predicted by FEM for radial buildup of magnetite and dented tube.

Fig. 10. Impedance plane trajectories predicted by FEM for axial buildup of magnetite.
CONCLUSIONS

The use of a numerical model for generating prototype signals for defect classification schemes represents a powerful approach. By combining the advantages of the Fourier descriptor method with the power and versatility of the finite element model a classification method which does not suffer from the limitations of being able to characterize only simple defects has been proposed.

REFERENCES


