System for Eddy Current Nondestructive Testing Based on Digital Signal Processing and Neural Networks

T. Chady and M. Enokizono
Faculty of Engineering, Oita University, 700 Dannoharu, Oita 870-1192, Japan

(Received Oct. 15, 1998; Accepted Jan. 21, 1999)

This paper proposes a new system for multi-frequency testing of conducting plates. Precise crack imaging was achieved by the use of spectrograms obtained from an eddy-current probe multi-frequency response and application of a neural network. Results showing very good sensitivity to small cracks in INCONEL600 specimens are presented.

Key words: non-destructive evaluation, eddy current sensors, neural networks, flaw recognition, inverse problem, digital signal processing.

1. Introduction

A considerable effort is underway to develop new eddy current systems for detecting and recognizing cracks. Both frequency-domain and time-domain techniques are developed. In this paper authors have proposed a new concept of multi-frequency system. A complex signal containing selected sinusoidal components was used for testing. In case of such signal an information content is greater than in a case of single-frequency signal. On the other hand the proposed technique is far faster than swept-frequency measurements. Time required for acquire the complex signal is the same as for single-frequency signals.

2. System description and operation

In order to achieve precise crack recognition, a new computer-controlled system for eddy current multi-frequency nondestructive testing was constructed. The experiences from the previous system [1] have been taken into account by the authors and significant improvements have been done. The new system can operate at any set of frequencies between 5Hz and 8MHz and is capable of making measurements with various sensors and techniques. It consists of the following main components:

- eddy current sensor,
- X-Y-Z scanning device,
- high performance data acquisition system (amplifier, anti-alias filter and A/D converter),
- excitation subsystem (wave synthesizer, and high speed power amplifier),
- pentium based computer with GPIB and VXI interface boards,
- computer program for instruments control and data processing.

A block scheme of the system is shown in Fig. 1. The whole system is controlled through the VXI and GPIB interfaces by a personal computer equipped with specially prepared software. The computer is also performing such tasks as digital signal processing of incoming signal and crack recognition.

One of the important elements of the system is a properly designed sensor. The authors have proposed two eddy current sensors. The first one (Fig. 2) is suitable for testing of thick conducting plates, while the second sensor (Fig. 3) is its optimized version, designed for detection of small flaws in thin INCONEL600 plates.

Fig. 1 Block scheme of the system.
The first sensor consists of an exciting coil and a set of search coils. All coils are wound on ferrite core shown in Fig. 2. The exciting coil has 200 turns (φ0.2mm), and each of the fourteen search coils has 100 turns (φ0.04mm). Multiple search coils enable to perform at once measurements in many points.

The second sensor (Fig. 3) has a similar construction, but the ferrite core is smaller and number of search coils is reduced to six. The exciting coil has 100 turns (φ0.2mm), and each of the six search coils has 100 turns (φ0.04mm).

A function synthesizer supplies excitation coil of the sensor through the high-speed power amplifier. A complex signal containing selected harmonic components is used in order to achieve information from number of frequencies.

The analog signals obtained from the search coils are converted into digital form by the data acquisition system. This system is a VXI device and consists of a multiplexer, a computer-controlled amplifier, anti-alias filter and a high performance A/D converter. The high speed (20 megasample per second) and excellent dynamic range (32 bit resolution) of the converter are crucial for the performance of the whole system. The speed is necessary to achieve proper signal representation. The resolution is also necessary, because generally the changes of the signal caused by a defect are very small in comparison with the level of background signal.

Noise and other artifacts are introduced by several internal and external sources, including transducer and instrumentation. In order to remove influence of noises and to extract the amplitude of main components from the measurements, signal-processing algorithms have been applied. Estimation of power spectra is useful in variety of applications, including the detection of signals buried in wide-band noise [2]. Authors have also used this technique for amplitude estimation of the each frequency component. Then a digital low-pass infinite impulse response filter processes the resulting signals in order to remove high frequency fluctuations. The applied anti-causal filter performs zero-phase digital filtering by processing the input data in both the forward and reverse directions. After all mentioned operations, the resulting signals were used for creation of spectrograms.

Example of the spectrogram is shown in Fig. 4. The spectrogram is a two-dimensional display of the relative amplitude of the frequency components of a signal from the single search coil over the sensor position. After analysis of spectrogram a set of selected parameters ("Amplitude_{max}", "Frequency_{max}", "Δx", see Fig. 4) is calculated and is passed to the input of a neural network used for crack recognition.

3. Experimental results

In order to demonstrate advantages of the system a set of experiments was carried out. The test specimens consisted of a set of 5 mm thick plates of SUS304 and a set of thin (1.25 mm) plates of INCONEL600. The INCONEL600 specimens have the same thickness as the tubes used in a steam generator of pressurized nuclear power reactors.

For the SUS304 plates the width of the crack was 5 mm, the length was 10 mm, while the relative depth was from 20% up to 80%.

For the INCONEL600 specimens [3] the flaws are made by EDM. Each flaw is a notch of width 0.2 mm and the length 2 mm, while the relative depth is from 20% up to 100%.

Regarding position of the flaw, two main categories of flaws can be distinguished: inner flaws (IF), when the flaw and the probe are from the same side of conducting plate, outer flaws (OF) when the crack and the probe are on the opposite side, and finally a penetrating flaw (PF).

The measurements were done by scanning the probe along the line perpendicular to the slot axis in steps of 0.5 mm. The liftoff (the gap between the specimen and the sensor) was measured to be 0.2 mm.
Fig. 5 Spectrograms and parameters of spectrograms for inner and outer cracks with various depths (thick plate of SUS304).

Fig. 6 Spectrograms and parameters of spectrograms for inner and outer cracks with various depths (thin plate of INCONEL600).
The measurements were made using the multi-frequency excitation signal consists of thirteen sinusoidal components having frequencies from 2kHz up to 26kHz for the SUS304 plates and sixteen sinusoidal components having frequencies from 10kHz up to 160kHz for the INCONEL600 plates.

The spectrograms for the SUS304 plates are presented in Fig. 5 and for the INCONEL600 plates in Fig. 6 respectively. From these figures it is possible to observe that the data enable very precise determination of a crack position and depth and can be used successfully for cracks identification.

4. Neural network for a crack recognition

In case of the presented results of measurement it is possible to determine the crack type and depth directly from the spectrogram, but in order to achieve completely automatically working recognition system an application of simple neural classifier was proposed. A conventional (fully connected) feed-forward network was used to solve the inverse problem of crack identification. The schematic view of the network is shown in Fig. 7. In the proposed net there are two layers with connections to the outside world: an input plane consists of 3 units, which receives parameters extracted from the spectrograms and three output neurons which gives the information about crack width, depth and position (inner flaw, outer flaw). The main design parameter of the network is the number of hidden neurons, which guarantee the desired degree of accuracy. There is no established rule to strictly determine how many neurons are needed to obtain a given degree of accuracy [4]. After some experiments it was found that the minimal number of hidden units is two neurons.

The neural network used for crack recognition was trained with the data achieved from measurements. All the data were divided into three parts: training set, validation set and the test set. The learning should be stopped at the minimum of the validation set error. After finishing the learning phase, the net was finally checked with third data set, the test set.

Because simple back-propagation is very slow, after some experiments the Levenberg-Marquardt method was selected as the most sophisticated rule. Figure 8 shows how the sum of squared errors over all training vectors converged as the training epochs occurred. It took only 180 epochs for the network to achieve error less than the goal of $10^{-4}$. The resulting network has a sum-squared error of $10^{-4}$. All calculations were performed using a neural network simulator on a personal computer with 300 MHz Pentium processor. The learning process took only four seconds. After training a network was able to classify all kinds of cracks properly. Thanks to the ability of neural networks to generalization, even for untaught cases the crack classification was proper.

5. Conclusions

The principal conclusion drawn from the experiments is that the proposed multi-frequency method and the system seem to be very promising for the evaluation of crack properties.

The advantages offered by the system can be summarized as follows:

- As a result of using multi-frequency excitation the response to several different frequencies can be measured at once.
- Testing frequencies can be freely selected according to user requirements.
- Information obtained from the range of frequencies collected in one spectrogram enables the precise flaw depth and shape identification.
- The same instrumentation as for single frequency method is sufficient for our technique.
- The system offers high speed of operation.
- Very good sensitivity and resolution were confirmed by measurements.

References