DESIGN OF AN NDE INTEGRATED DATA ACQUISITION SYSTEM (NIDAS)

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ABSTRACT. NDE techniques are each characterized by their individual strengths and limitations that are dictated by the underlying physics. Data Fusion techniques that combine information from multiple sensors can help in exploiting the capabilities of multiple NDE modalities. Hence, there is a need for a system that can perform multi-sensor data acquisition and processing. This paper describes an NDE Integrated Data Acquisition System (NIDAS) that can perform an ultrasonic and eddy current testing simultaneously. C-scan images from both inspections may be obtained from the same scan operation, and these images are spatially correlated. Images obtained in this manner are well suited for data fusion applications and other image and data processing algorithms for enhancing the testing results. A data fusion example is presented using an eddy current and an ultrasonic C-scan image obtained from the NIDAS. The result shows significant enhancement on the defect profile.

INTRODUCTION

Many forms of excitation energy have been used in NDE [1], [2] such as electromagnetic, ultrasonic, thermal, etc. and each technique is characterized by its individual strengths and limitations. For instance, ultrasonic NDT provides accurate information about the location of a defect but lacks resolution in its shape and size, whereas eddy current signals contain relatively more information about the defect profile. One solution to enhance the inspection result is to apply data fusion techniques [3], [4] to combine the information present in the C-scan images obtained from each inspection method in a synergistic manner. The result is more precise information on the defect size, profile and location. This paper describes the development of a system that focuses on the electromagnetic (eddy current) and ultrasonic NDT methods.

The NDE Integrated Data Acquisition System (NIDAS) not only provides a useful tool to perform ultrasonic or eddy current testing, the system also allows both inspections to be carried out simultaneously. C-scan images from both inspections may be obtained from the same scan operation, so that the images are spatially registered. The following sections describe the characteristics of ultrasonic and eddy current NDE, and an integrated inspection system such as the NIDAS. A description of the NIDAS hardware and software is then given, followed by a discussion of a data fusion algorithm. The paper concludes with an example showing the resulting image when applying the data fusion algorithm to an eddy current and ultrasonic image obtained from the NIDAS.
ULTRASONIC AND EDDY CURRENT NDE AND DATA FUSION

Ultrasonic NDE

Two physical quantities of interest in an ultrasonic inspection are the amplitudes of the received signals and the time-elapses, or the time-of-flights (TOFs), between the incident and the received signals. While the signal amplitude can be related to the flaw size [2], the time-of-flight information maybe combined with the velocity of the ultrasonic wave in the test object to obtain the location of the flaw.

Ultrasonic wave propagation in a solid is described by the general motion equation [6]:

\[ \nabla \cdot \tau + \mathbf{F} \rho = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \]  

where \( \tau \), \( \mathbf{F} \), \( \rho \), and \( \mathbf{u} \) represent the stress-tensor, body force, material density and displacement vector, respectively. Ultrasonic waves propagate deep into a test specimen and are, therefore, suitable for detecting deeply embedded flaws. At the interface between two inhomogeneous media, a traveling wave is partially reflected according to Snell’s Law. Unfortunately, as the wave travels through the couplant and test object, the signal is attenuated and contaminated by various noise sources such as the speckle noise. Post-processing of the signal is required to improve the SNR and extract the useful information.

Eddy Current NDE

Eddy current NDT is commonly used for inspecting conducting materials. The eddy current signal shows the real and imaginary components of the complex probe voltage as the probe is moved across a defect area. This change in impedance can be measured and used to deduce the size, shape, and location of a defect.

Eddy current phenomena is governed by the linear diffusion equation:

\[ \frac{1}{\mu} (\nabla \times \nabla \times \mathbf{A}) = \mathbf{J_s} - \sigma \frac{\partial \mathbf{A}}{\partial t} \]  

where \( \mu \) is the permeability (=\( \mu_r \mu_0 \)) and \( \sigma \) the conductivity of the material. The magnetic vector potential, \( \mathbf{A} \), is related to the magnetic field, \( \mathbf{B} \), by \( \mathbf{B} = \nabla \times \mathbf{A} \). \( \mathbf{J_s} \) is the source current density in the coil. The diffusion process produces signals that are relatively noise-free but contains comparatively less information regarding the test specimen. The process is also limited to the skin depth of the material.

NDE Data Fusion

The ultrasonic and eddy current NDE techniques each offer inspection capabilities and limitations that are dictated by the underlying physics. For example, an ultrasonic C-scan image of a test specimen with a narrow surface-breaking crack may offer excellent resolution and a well-defined defect shape. Unfortunately, such an image typically offers little information for inferring the crack depth profile. An eddy current C-scan image, on the other hand, offers a wider dynamic range in gray levels to provide information on the profile of the defect. However, the large size of the probe in relation to the width of the flaw typically results in severe blurring of the defect boundary. Since the data provided by the two images are complementary in nature, data fusion methods offer the potential for improving defect characterization.
The NIDAS provides a platform for performing ultrasonic and eddy current inspections both separately and simultaneously. The state-of-the-art computer user interface allows C-scan images to be obtained for both techniques from a single pass over the test object. The resulting images are spatially correlated. Images obtained in this manner are well suited for data fusion applications and other image and data processing algorithms for enhancing the testing results.

THE NDE INTEGRATED DATA ACQUISITION SYSTEM (NIDAS)

The NDE Integrated Data Acquisition System, NIDAS, is a PC-based inspection system. It consists of three modules: The eddy current system is based on an ISA PC card and resides within the PC. The ultrasonic system consists of both internal and external components to the PC. The motion controlling system is an external unit. Its purpose is to position the eddy current probe and ultrasonic transducer and to move them according to predetermined scan plans. The three modules may work independently, cooperatively, or simultaneously. Note that individual components of these modules may be replaced upon availability of new technology or changing application requirements, as long as the proper software drivers and interface modules are developed and integrated into the software architecture.

NIDAS Hardware

At the heart of the NIDAS is a 300 MHz Pentium II MMX PC with 128 MB of memory and 8 GB of hard disk space. The ultrasonic inspection system consists of a Panametrics 5052PR pulser-receiver as an external excitation source, a Gage Applied Sciences Inc. CompuScope 2125 ISA analog-to-digital converter (ADC) PC expansion card, and an ultrasonic transducer. The block diagram of the ultrasonic inspection system is shown in Figure 1. The signal from the T/R (transmitter/receiver) terminal of the pulser-receiver is delivered to both the transducer and the ADC, and the trigger output of the 5052PR is used to trigger the ADC. The signal sampled by the ADC contains the excitation pulse launched, as well as the response received by the transducer. Appropriate windowing algorithms based on the time-of-flight information of the signals have been developed to isolate and display either or both signals.

The eddy current inspection system is based on the IMTT (Innovation Materials Testing Technology, Ames, Iowa, USA) ECSF2 eddy current system ISA PC board. The choice of eddy current probe for this system depends on the test configuration and the specimen being inspected. The default is an absolute/differential pencil probe.

For three-dimensional movement control, the NIDAS uses the Takano DC-3000 Triplicate Dimensional Controller. The controller has movement ranges of X-axis: -2 to 169 mm, Y-axis: -6 to 303 mm, and Z-axis: -14 to 68 mm, and is controlled by the PC through both the RS-232C and parallel interfaces.

A custom probe mount (Figure 2) is constructed to secure the eddy current probe and the ultrasonic transducer for simultaneous data acquisition by the ultrasonic and eddy current...
FIGURE 1. Block diagram of the NIDAS.

FIGURE 2. The custom probe mount constructed for the NIDAS. The top bracket is for an ultrasonic transducer and the bottom one is for an eddy current probe. The distance between the mount centers is 33 mm.

inspection systems. The design is such that the probes are self-centered inside the mounts. The known distance between the two probes establishes a spatial correlation between the two test signals.

**NIDAS Graphical User Interface**

The NIDAS graphical user interface structural block diagram is shown in Figure 3. The main frame (MF) structure is responsible for maintaining the GUI's appearance and coordinating all user interactions (menu selections and updates, toolbar buttons interactions, etc.). The main frame window coordinates and initiates activities for the three internal modules: The eddy current, ultrasonic, and tri-axial motion controller modules. These modules correspond directly to their hardware counterparts. The software contains 10 distinct views, belonging to one of the four systems indicated in parenthesis: The main frame window (MF), complex strip-chart (EC), A-scan (EC), C-scan (EC), Impedance Place (EC), Image (EC), Scope view (US), A-scan (US), C-scan (US), Image (US, same as EC), and the motion controller manual control panel (TXMC). The windows related to eddy current testing are shown in Figure 4.

**DATA FUSION (LMMSE) ALGORITHM**

This section describes the signal processing module for fusing data from multiple sensors or NDE sources. Assuming that both the signal $s(t)$ and noise are real, stationary random processes with known spectral characteristics, the linear system for data fusion consists of $N$ filters whose outputs are combined together to generate the fused image.
\( \hat{s}(t) \) as shown in Figure 5. The linear filter that minimizes the mean square error is called the linear minimum mean square error (LMMSE) filter.

The equations for the input and output of the fusion or restoration filters can be written as

\[
x_j(t) = y_j(t) + n_j(t) = h_j(t) * s(t) + n_j(t)
\]

\( \text{for } 1 \leq j \leq N \) \hspace{1cm} (3)

\[
\hat{s}(t) = \sum_{i=1}^{N} g_i(t) * x_i(t) = \sum_{i=1}^{N} \int g_i(t - \lambda) * x_i(\lambda) d\lambda
\]

\( \text{for } \lambda \) \hspace{1cm} (4)

where \( x_j(t) \) is the input to the fusion filter, \( y_j(t) \) is the sensor output, \( n_j(t) \) is the noise term, and \( h_j(t) \) and \( s(t) \) are the sensor transfer function and the true data, respectively.

The mean square error (MSE) is then defined by

\[
\text{MSE} = E\left[ s(t) - \hat{s}(t) \right]^2
\]

Minimization with respect to the restoration or fusion filter parameters results in a linear set of equations given by

\[
\text{FIGURE 3. The NIDAS graphical user interface structure block diagram.}
\]
FIGURE 4. The NIDAS application showing the eddy current strip chart, impedance plane, and hardware device (ECSF2) control windows.

FIGURE 5. Block diagram of the LMMSE data fusion algorithm.

\[ E \left[ s(t) - \sum_{j=1}^{N} \int g_i(\lambda) x_i(t - \lambda) d\lambda \right] x_j(\xi) = 0 \quad 1 \leq j \leq N \quad (6) \]

Defining the cross correlation function \( R_{x,y}(\tau) = E[x(t + \tau) y(t)] \), we have

\[
\begin{align*}
R_{x,y}(\tau) &= R_{x_1,y_1} + R_{x_2,y_2} + \cdots + R_{x_N,y_N} \\
R_{x,y}(\tau) &= R_{x_1,y_1} + R_{x_2,y_2} + \cdots + R_{x_N,y_N} \\
R_{x,y}(\tau) &= R_{x_1,y_1} + R_{x_2,y_2} + \cdots + R_{x_N,y_N} \\
\end{align*}
\]

(7)

Substituting back in (6) and taking Fourier Transform of both sides, we get,
where $S_{xy}$ is the power spectrum density of $y$ and $S_{s,y}$ is the cross-spectrum density between $s$ and $y$. Letting

$$\Gamma(s) = \sum_{i=1}^{N} G_i(s) H_i(s)$$

and using the relation

$$S_{y,y}(s) = H_j(s) H_j^*(s) S_j(s)$$

the equation for the fusion filters can be written in terms of the power spectral densities as

$$G_j(s) = \frac{S_j(s) H_j(-s)}{S_n(s)} (1 - \Gamma(s))$$

For $N=2$, we have

$$G_1(s) = \frac{H_1(-s) S_n(s)}{|H_1(s)|^2 S_n(s) + |H_2(s)|^2 S_n(s) + \frac{S_n(s) S_n(s)}{S_s(s)}}$$

$$G_2(s) = \frac{H_2(-s) S_n(s)}{|H_1(s)|^2 S_n(s) + |H_2(s)|^2 S_n(s) + \frac{S_n(s) S_n(s)}{S_s(s)}}$$

In the case of two dimensional discrete image data, the fusion filters can be expressed

as $G_j(z_1, z_2) = \frac{S_j(z_1, z_2)}{S_n(z_1, z_2)} \frac{H_j(z_1^{-1}, z_2^{-1})}{1 + \sum_{i=1}^{N} S_j'(z_1, z_2) |H_j(z_1, z_2)|^2}$

RESULTS

Figure 6 shows the NIDAS application displaying an ultrasonic and eddy current C-scan images side-by-side. The data fusion technique described before is applied to these images and the resulting image shows the defect with sharp shape definition as well as wide depth information (Figure 7).

CONCLUSIONS

The NIDAS provides a useful platform for performing ultrasonic and eddy current inspections both separately and simultaneously. The state-of-the-art computer user interface allows C-scan images to be obtained for both techniques from a single pass over the test object. The resulting images are spatially correlated. Data and images obtained in this manner are well suited for data fusion applications and other image and data processing algorithms for enhancing the test results. Data fusion techniques have been applied to an eddy current and an ultrasonic C-scan image obtained from the system and the resulting image shows a clear defect shape and depth profile, displaying significant enhancements to the original images.
FIGURE 6. An example of the NIDAS application displaying an ultrasonic and eddy current c-scan images side-by-side.

FIGURE 7. The eddy current C-scan image on the left shows a wide gray-scale range for depth information, but the edges are too blurry for precise defect shape identification. The ultrasonic C-scan image in the center displays excellent resolution and definition of the crack, but offers little information on the depth of the defect. Applying data fusion techniques [3]-[4] to the C-scan images yields the image on the right with sharper edges and enhanced defect depth information.

REFERENCES