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Research on inverse problems in materials science and engineering

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Abstract

The role of inverse problems in the characterization of materials is discussed. Four such problems are described in detail: deconvolution for acoustic emission, tomographic reconstruction of temperature distribution, electrical-conductivity profiling and inverse scattering. Each exploits a priori information in a different way to mitigate the ill-conditioning inherent in most inverse problems.

Advances in born inversion

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Abstract

The 1-D Born Inversion Technique is well established as a method which gives defect radii from pulse-echo ultrasonic measurements. Recent developments give the diameter of a flaw from measurements in the Born Radius/Zero-of-Time Shift Domain (BR/ZOTSD) without the explicit need to select a correct zero-of-time for the inversion. A signature for the flaw is obtained by plotting the estimated flaw radius as a function of a certain time shift, (shifting the zero-of-time). The signature does depend on transducer bandwidth, but the resulting diameter is, to a larger extent, insensitive to the bandwidth of the transducer employed. A corresponding BR/ZOTSD signature has been obtained for sizing voids. This work represents a unification of many of the features considered in earlier studies of Born Inversion with those found in time-domain sizing techniques, such as 'SPOT'. The accuracy to which a flaw size estimate can now be given is significantly improved using this extension to the process of 1-D Born Inversion and this is demonstrated with analytical, numerical and experimental data.

Modern signal processing

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Abstract

In this paper, we present some aspects of modern signal processing. The issues considered include stochastic modeling, linear prediction, and the interrelationship between them. Computational aspects of these issues are also considered. Detection algorithms are described, which exploit the innovations representation of a stochastic process.

A split spectrum processing method of scatterer density estimation

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Abstract

The split spectrum processing method of estimating scatterer concentration and concentration gradients using the data of a single received waveform is reported. A wide-band received spectrum is partitioned into separated frequency bands which are normalized and filtered by Gaussian windows. The estimation algorithm is based on a theory which states that the squared ratio of the sample mean of the amplitudes produced by the split narrow-band signals to its standard deviation is a measure of scatterer concentration. The theory presented is shown to be confirmed by experiment.

Spectral and spatial processing techniques for improved ultrasonic imaging of materials

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Abstract

As with other detection methods, ultrasonic non-destructive testing techniques are limited in their ability to differentiate the signal of interest from the background noise. Detection of targets is particularly difficult when the noise resulting from the unwanted stationary reflectors (i.e. grains in metals, clutter in radar, and speckle in laser) becomes significant. This type of noise is coherent and its effects cannot be reduced effectively by conventional techniques such as time averaging.

The objective of the work presented here is to improve the detectability of defects in large grained metals. In previous work, frequency and spatial diversity techniques have been utilized in conjunction with several nonlinear detection algorithms to suppress the grain echoes with respect to the flaw echo in one-dimensional A-scan applications. Here, the frequency and spatial processing techniques developed in earlier work are extended to B-scan imaging. Furthermore, the detection algorithms are analyzed both theoretically and experimentally to determine the relative performances. The experimental data obtained from stainless steel samples are used to demonstrate the gain echo suppression capability of each algorithm and to verify the theoretical results.

Signal processing of ultrasonic backscattered echoes for evaluating the microstructure of materials - a review

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Abstract

The microstructure evaluation of materials using ultrasonic backscattered echoes has significant practical implications. Ultrasonic backscattered grain echoes are random signals which bear information related to the attenuation caused by scattering and absorption. The variation of attenuation as a function of position and frequency represents changes in the scattering cross-section and absorption effects of grains. We present a statistical model of backscattered signals which is used for developing signal processing techniques in both time and frequency domain. The attenuation in the backscattered signal is evaluated by performing temporal and spatial averaging. The spectral shift in the backscattered signal is characterized using moment analysis. Furthermore, frequency-dependent attenuation is estimated by applying cepstral processing. Experimental results using steel samples of different grain sizes are in close agreement with theoretical predictions.

High resolution deconvolution of ultrasonic traces

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Abstract

Ultrasonic inspection techniques are of considerable importance in the nondestructive evaluation of laminar and composite materials. In the detection and localization of flaws, it is frequently desirable to enhance the resolution of the raw B-scan data. In this report we describe the principles and performance of procedures for improving the temporal resolution of the data. The methods are one-dimensional and are applied to successive traces (A-scans).

Two techniques for high resolution deconvolution are investigated. They are based on the assumption that the underlying reflection series is sparse, i.e., contains relatively few non-zero spikes. The first method is a simple spectral extrapolation procedure. Here the Fourier transform of the deconvolved data will consist of a small number of complex exponentials, for which autoregressive filter coefficients (in a region of high SNR) may be computed using the Burg algorithm [1]. This filter may then be used to extrapolate the transform outside this high SNR region, thereby achieving a broadband result. The second method is a recently developed deconvolution technique based on curve-fitting in the L1 (least absolute values) norm. In this procedure the reflection series is built up one-at-a-time until a specified maximum number of spikes is reached or a desired fit to the trace is achieved.

These and other processing schemes were incorporated into an integrated software system for simulation and analysis, developed for VAX/VMS computers. Currently we are developing a fast B-scan processing system, making use of a Compaq 386 microcomputer and a TMS 32020 signal processing card; this system is designed to yield high resolution B-scan images in real time.

Non-destructive evaluation in the time-frequency domain by means of the Wigner-Ville distribution

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Abstract

In a number of NDE problems, parameters of interest are related to both temporal and spectral signal descriptions. It is then proposed to introduce mixed tools which consider time and frequency simultaneously. Among different possible approaches, it is justified that time-frequency distributions related to the Wigner-Ville transform are of special interest. A concrete example, stemming from an underwater acoustics experiment, is provided for supporting the usefulness of the proposed method.

Pulse shaping and extraction of information from ultrasonic reflections in composite materials

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Introduction

Most ultrasonic inspections of materials involve sending elastic waves generated by a transducer through the investigated material, and monitoring either the transmitted waves as appear on the other side of the material, or the reflected waves which return back to the first side. Information about the state of the material is obtained by analyzing the received waves for global acoustic properties as well as local properties that may result from acoustic discontinuities such as defects in the material. Such analysis becomes more difficult when investigating composite materials. These materials have a complex structure, a complex acoustic wave propagation, and are limited to inspection by waves with relatively low frequencies due to high attenuation at high frequencies. All these contribute to more complex waveforms where overlapping of different signals make identification and investigation of discrete events very difficult. Digital signal processing can be used to help in this matter, increase the resolution, and facilitate analysis, as demonstrated here through description of three cases.

Signal processing for eddy current nondestructive evaluation

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Introduction

Eddy current techniques of nondestructive testing have grown considerably more sophisticated ever since Hughes [1, 2] showed conclusively that the method can be used with success to characterize conductive materials. Despite the antiquity of the method, progress was limited until recent years, when a combination of factors contributed to the growth in the number and variety of applications. These factors include advances in instrumentation and a better appreciation of the underlying physical process. The availability of relatively inexpensive analog and digital signal processing devices have contributed to the development of instrumentation with unprecedented levels of sensitivity. In addition the entry of microprocessors into the arena has rendered such mundane tasks as calibration and data base management less wearisome. The development of mathematical models characterizing the process [2-6] has not only led to a better understanding of the underlying physical mechanism but has also contributed to better transducer and experiment design [7]. One of the most important contributors to the growth in the popularity of the method has been the development of signal processing techniques capable of extracting information relevant to the properties of the material under test from the signal [8]. The drive behind the effort to develop signal processing techniques has also stemmed from a desire to automate the inspection procedure and minimize human involvement. This paper attempts to summarize some of the work done in the area of eddy current NDE signal processing. The coverage is not intended to be exhaustive. Instead, the paper merely attempts to provide a flavor of some of the techniques that have developed and implemented. Before we proceed further and discuss some of the signal processing methods, a brief description of the eddy current method follows.

Eddy current modeling and signal processing in NDE

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Introduction

Our multifrequency reconstruction algorithm is based on a rigorous electromagnetic model for eddy-current interactions with flaws in conducting tubes. The theoretical model for eddy-current interactions with flaws is conducting tubes. The theoretical model was originally developed for nonferrous (stainless steel) tubes and was published in the IEEE Transactions on Magnetics [1]. While the reader is encouraged to read [1] in order to understand the electromagnetic details of the model and algorithm, we will review the equations in the next section, and then concentrate on applying the algorithm to laboratory reconstructions.

The electromagnetic analysis leads to certain integral equations which give the components of the perturbed magnetic induction field in terms of the two-dimensional Fourier transforms of the conductivity distribution of the anomalous region at each of N_r layers within the cylinder wall. The objective is to invert these equations, i.e., to determine the conductivity distribution, given the measured induction field as input data.

The data is acquired by measuring the perturbed induction field with a two dimensional sensor array. We then take a two dimensional Fourier transform which gives us data at each Fourier pair (m, h), where m is the azimuthal spatial frequency and h the axial *spatial frequency*. This process is repeated at several frequencies which allows us to write down an equation for each frequency. If there are N_f frequencies, then we arrive at a system of N_f equations in N_r unknowns, in each couple (m, h). In the laboratory experiments to be described later, we used 25 frequencies ($N_f = 25$), starting at 100 kHz and ending at 5 MHz. The number of layers, N_r, was equal to ten.

High resolution spectral analysis NDE techniques for flaw characterization, prediction and discrimination

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Abstract

In this paper the feasibility of ultrasonic spectroscopy in nondestructive evaluation (NDE) is examined with the support of digital signal processing, modern spectral analysis and digital pattern recognition. The modern high resolution spectral analysis and related signal processing and pattern recognition techniques have demonstrated that the ultrasonic spectroscopy as pioneered by Otto Gericke can indeed solve many NDE problems which were previously very difficult to work with. Both theoretical analysis and computer testing of algorithms for the data available were conducted. The main new results presented in the paper are: (1) The Wiener filtering algorithms is three versions, and L1 deconvolution to determine the impulse response of the defect materials tested. The impulse responses are useful for flaw size estimation and feature extraction, as well as flaw characterization. (2) Spiking filter and time domain deconvolutions of multiple reflections which are closely spaced. (3) A complete listing of effective spectral domain and related features. A scatter plot is presented. (4) Development of wavelet transform for multiple scale representation, which is useful to provide features to distinguish different flaws. (5) Realization of above results in a Personal Computer. In fact, a whole range of signal processing and pattern recognition techniques has been realized. As the need for high accuracy NDE in complex materials increases, high resolution spectral analysis is becoming even more important to provide desired information from limited NDE data.

Automated ultrasonic system for submarine pressure hull inspection

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Abstract

To meet the increasingly demanding requirements for ultrasonic testing of submarine pressure hulls, a project was undertaken to design an inspection system that incorporated artificial intelligence signal interpretation and data logging capabilities in a workstation configuration that could be used by field inspectors. The system is described and some preliminary results of the use of the artificial intelligence system for signal classification are presented.

Key words: ultrasonics, non-destructive testing, artificial intelligence, pattern recognition, knowledge representation.

Pattern recognition of ultrasonic signals for detection of wall thinning

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Abstract

Detection of wall thinning in piping systems in power generating plants is becoming more important as the time in service increases and deterioration by corrosion and erosion accumulates. Acousto-ultrasonic testing combines the advantages of ultrasonic inspection with the remote monitoring capability of acoustic emission for detection of this type of materials deterioration. While acousto-ultrasonic inspection has been applied in resin-matrix composites, attenuation parameters used to characterize acousto-ultrasonic signals are less discriminating in metals. This preliminary investigation showed the feasibility of using pattern recognition methods to effectively interpret acousto-ultrasonic signals from sections of metal piping that have been subjected to wall thinning.

Key words: Acousto-ultrasonics, pattern recognition, artificial intelligence, nondestructive testing, corrosion testing.

Knowledge based systems in nondestructive evaluation

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Introduction

This paper discusses the application of knowledge based systems technology to problems in nondestructive evaluation (NDE). The Saft Image Interpretation Assistant (SIIA) is used as an illustrative example [1]. SIIA is a prototype knowledge based system designed to assist in making the operation of the Synthetic Aperture Focusing Technique (SAFT) Ultrasonic Inspection System more reliable and efficient [2].

The two primary motivations for developing SIIA were to insure that the SAFT system is used correctly and consistently and to assist in interpreting the results of a SAFT inspection. Our initial goal was to develop a system to assist in the interpretation of the images resulting from a SAFT inspection. As we started to identify the structure of the inspection problem, however, we realized knowledge based system technology could be more effectively applied to develop a system that is in essence an on-line procedure generator that guides a user through a SAFT inspection. When fully developed such a system could assist in proper setup of the inspection equipment for each of the steps in a SAFT inspection and in interpreting the inspection results for each step.

The first section of the paper describes the structure of the SAFT inspection problem. The next section discusses three forms of knowledge: procedural, structural, and inferential as they relate to the SAFT problem. The final section discusses the implications of this type of system for other NDE techniques and applications.

Limited-angle image reconstruction in non-destructive evaluation

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Abstract

The practice and the theory of image reconstruction in conventional x-ray computerized tomography (CT) is briefly reviewed. Limited-angle CT is introduced where it is shown that scanning in a restricted angular range results in missing information, which in term causes the problem to become underdetermined. The use of generally available a priori information can compensate for the missing information and therefore improve the reconstructed image. An efficient iterative transform algorithm which utilizes the a priori information in conjunction with the limited-angle x-ray data to reconstruct the object is described. The object is transformed back and forth between the object space and the projection space, being corrected by the a priori information in the object space, and the limited-angle known projections in the projection space. The use of the convex hull of the object in image reconstruction is introduced, and the procedure for the construction of the hull from the x-ray data detailed. The use of more specific a priori information is shown to further improve the reconstructed image. Finally, the applications of limited-angle image reconstruction to the reduction of scan time and dosage in fan beam scanning, image improvement in conventional digital tomography, and ultrasonic flaw characterization are discussed.

The effects of limited data in multi-frequency reflection diffraction tomography

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Abstract

This paper examines the implications of reconstruction from limited spatial frequency coverage in multi-frequency reflection diffraction tomography. The inversion equation in reflection diffraction tomography is presented. It is shown that the resultant multi-frequency data provides coverage in a one-quadrant of the spatial frequency domain. This coverage yields accurate information regarding the surface structure of the object under study.

A 3-D image segmentation algorithm

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Abstract

We present a 3-D segmentation algorithm to extract object surfaces from Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) scans. The algorithm is formulated in the framework of Mathematical Morphology. A priori knowledge of the approximate location of the object surface is communicated to the algorithm via the definition of the Search Space. The algorithm uses this definition of the Search Space to obtain the Surface Candidate elements. The search space specification reduces the computational cost and increases the reliability of the detected features. The detected surface is represented as a hierarchical combination of patches.

Processing of thermal images for the detection and enhancement of subsurface flaws in composite materials

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Abstract

Subsurface imaging using thermal wave generated either by line heating with lateral displacement of the part to be inspected or full-field heating with no displacement is an attractive approach for the NDE of composite materials. Proper detection of flaws, such as delaminations or unbonds require dedicated thermographic image processing.

In this paper we will present recent work done at our Institute on the detection and enhancement of unbonds in aluminum to foam laminates. Also quantitative characterization of flaws in graphite-epoxy laminates using specially developed image processing and modelling will be presented. Emphasis will be given to either time-domain or space-domain image processing methods for precise and reliable defect visualization.

Laplacian pyramid image data compression using Vector quantization

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Abstract

With the increased use of digital images in nondestructive evaluation (NDE) of materials, effective image compression and coding techniques are now much needed in NDE.

This paper describes a hierarchical organization of multiple-level processors for bottom-up image processing. Laplacian Pyramid Structure, and the quantization transform techniques: Vector Quantization Transform which are used on different spatial frequency bands to compress and encode the images.

The Laplacian Pyramid Structure first removes the nearest neighborhood pixel-correlation, or redundancy. At each level the image is already a compressed date since Laplacian image has low variance and entropy and each level image may be represented at very low sample density. The second step of data compression is achieved by Vector Quantizer, which is used on each Laplacian pyramid level to remove the redundancy and encode the images except for the highest level. Vector Quantization Transform has to have an appropriate codebook set. Therefore an iterative optimization approach is needed to build up this "good" codebook set. Finally, we use a Histogram Specification technique to align the reconstructed image with original image.

By adopting this multiple-level encoding model concept, the coding scheme can vary the coding filter to match the local characteristics of the testing image. Significant coding improvement can be obtained at the expense of a slight additional transmission rate for the model information. Experimental results on two different image sets indicate that the vector quantization technique employed can save about 75 % of time required by the traditional Linde-Buzo-Gray algorithm.

Parameter estimation in array processing

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Abstract

The paper deals with signal processing methods for the outputs of an array of sensors which sample a wavefield. The purpose of this signal processing is to obtain insight into the structures of the waves traversing the array. For example, location parameters of sources generating signals which are transmitted by the waves and spectral properties of these signals have to be measured. A typical application is sonar, where the sensors are hydrophones in the ocean and the signals are ship noise or echos. Signal processing in such sense is called array processing. Classical methods are known as beamforming which can be motivated, e.g. by spectrum estimation for wavefields. Limited apertures of the arrays result in limited resolution of beamforming. Then, location parameters of sources not well separated cannot be estimated by inspection of the beamformer output. Therefore, parametric statistical models and suitable parameter estimation methods have been developed. We review certain asymptotic distributional properties of the array output in the frequency domain and investigate maximum-likelihood estimates and corresponding numerical procedures. We also discuss possibilities for estimating the number of sources. We report of numerical experiments on the accuracy of simultaneous estimations of bearings, ranges and spectral powers of sources and compare with other high-resolution methods. The applicability of the methods to ultrasonic NDE is discussed.

Role of peak detection and parameter estimation in nondestructive testing of materials

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Abstract

In this paper a number of important aspects of the signal analysis and processing task in ultrasonic nondestructive evaluation of materials is discussed. We focus our attention on the pulse-echo method. A brief review of some available frequency and time domain techniques for flaw detection and characterization is given. It is important to realize that a combination of features are required for proper defect identification and subsequent characterization. A summary of potentially useful features is reviewed in the paper.

Nondestructive evaluation using the ultrasonic pulse-echo method is strikingly similar to a number of other application areas, including underwater exploration using the shallow seismic technique. As a result, techniques available for marine geophysical signal processing using underwater acoustic methods for seismic signal analysis and interpretation on the basis of reflections and multiple reflections from the sea-bed and the underlying media are described in the paper. This is done with a view to possible transfer of some useful procedures to the ultrasonic NDE area.

The main problem of marine seismic exploration is briefly described, and the process of relating signal model parameters to physical properties of the media traversed is discussed. Emphasis is given to the role of peak detection and parameter estimation in enhancing the identification process. A number of information extraction algorithms that are central to the interpretation process are presented. In particular, we treat delay and amplitude parameter estimation using two methods. In the first, a combined cross-correlation minimum variance filter is employed. In the second a linearized recursive estimation process is useful in the parameter estimation task.