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Quantitative nondestructive evaluation

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Abstract

Quantitative Nondestructive Evaluation (QNDE) provides techniques to assess deterioration of a material or a structure, and to detect and characterize discrete flaws. It plays, therefore, an important role in the prevention of failure. QNDE techniques are used in processing, manufacturing and for in-service inspection. QNDE is particularly important for the in-service inspection of high-cost and critical load-bearing structures whose failure could have tragic consequences.

In this paper, we briefly review the most important techniques, and then we focus the discussion on quantitative ultrasonics, particularly for crack detection and for the determination of elastic constants. The important role of measurement models is emphasized. New techniques in quantitative ultrasonics are discussed, including laser-based ultrasonics and acoustic microscopy. The possible applications of neural networks are indicated. Attention is also devoted to the probability of detection concept and its relation to probabilistic fatigue methods and fatigue reliability. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Methods of quantitative nondestructive evaluation (QNDE) are needed to meet requirements for reliability of materials, structural components and structures. These methods play an increasingly significant role in control of material processing, and pre-assembly validation, in-service monitoring and maintenance of structures.

Nondestructive testing was once an empirical technology based on the use of off-the-shelf equipment that produced data for correlation with benchmark results by the subjective judgment of operators. For simple applications, quite acceptable results were obtained in that manner for many years. However, to deal with more advanced applications, QNDE has become an engineering discipline which encompasses quantitative measurement techniques, physical models for computational analysis, statistical considerations, quantitative designs of measurement systems, specifications for flaw detection *and*

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characterization, system validation and performance reliability. The field also has important interfaces with materials engineering, reliability analysis, component design and manufacturing and maintenance procedures.

The evolution from non-destructive testing to quantitative non-destructive evaluation has been driven by the demand for cost reductions in the life-cycle management of structures. Fracture mechanics considerations dictate the need for techniques to detect, with sufficient certainty, flaws that are larger than an allowable size. This means that a structure should be designed to permit suitable inspections, and that the probability of detection (POD) of specified flaws with a specific technique should be in an acceptable range. The incorporation of NDE considerations in the design stage simplifies life-cycle management and improves safety of a structure once it is in service. Non-destructive evaluation techniques also make it possible to control manufacturing, particularly material processing techniques. Very considerable potential economic benefits continue to demand better NDE techniques for process control.

QNDE is particularly important for the in-service inspection of high-cost structures whose failure could have tragic consequences. Examples are aircraft, nuclear reactors and bridges. Trustworthy in-service inspection techniques are becoming increasingly needed as this country's civilian infrastructure and its transportation equipment and military platforms are becoming older. At this point it is expected that many of the systems that were built twenty, thirty or more years ago will not be replaced in the near future by next generation structures and equipment. Consequently these aging systems will have to be kept in service well into the next century. This is feasible, provided that adequate measures are taken to prevent poor performance, inadequate safety and increasingly expensive maintenance. The need for extended life expectancy does, however, raise the technical challenge that defects and material deterioration must be detected before failures occur.

Flaws and defects are introduced into materials during processing and they develop in structural systems during service. As time goes on, materials deteriorate, metals as well as polymer-based composites, and fatigue, corrosion and other degradation mechanisms may severely compromise the structural integrity and effective performance of systems. The degree to which this deterioration can be allowed has to be determined by appropriate studies of material behavior and failure analysis, and by the judicious use of nondestructive evaluation. A good program of life extension of aging structures can obviously save any organization millions of dollars. It will lead to the prevention of undesirable failures and it will be very important for in-service performance of structures.

Occasionally the world is reminded that aging structures may fail catastrophically if appropriate measures are not taken. For example, the potential perils of flying aging aircraft jumped into the public's consciousness in April 1988 when an Aloha Airlines 737 lost the upper front part of its fuselage, twenty thousand feet above the Pacific. A cabin attendant, who was standing in the aisle, lost her life, but the pilot managed to land the seriously damaged airplane. Although the manufacturers and the airlines had known for some years that many aircraft were exceeding their original design lives, and a number of actions had been taken with regard to aircraft inspection and maintenance procedures, the accident was a traumatic event. To the general public the advanced age of many in-service airplanes came as a surprise, and April 1988 marks a significant increase of the public interest in the airworthiness of the commercial aircraft fleet. The Aloha accident gave rise to an extensive program of research, development and technology transfer of methods to inspect aging aircraft, funded by the Federal Aviation Administration. Since that time similar programs have been started by NASA and the Air Force. A summary of the research and development strategy for the USAF aging aircraft program has been given in a recent National Research Council report (N.R.C., 1997). The report highlights and prioritizes key research areas. NDE measurements of property degradation in aging reactor components have been discussed in a report by the U.S. Nuclear Regulatory Commission U.S.N.R.C. (1995).

For specificity this paper focuses on the evaluation of materials properties and on the detection of cracks. We will also briefly consider the use of nondestructive evaluation in reliability considerations.

2. Techniques of QNDE

There are many techniques of quantitative non-destructive evaluation. Most are concerned with point-measurements, which may, however, be combined with scanning procedures to provide information over an area or a spatial region. In order that such scanning procedures will be carried out in a reasonable time-span, a high degree of automation and advanced data processing is required. Artificial intelligence techniques, either neural networks or expert-systems, also are expected to find more frequent application. Furthermore, it is expected that full field techniques such as thermal wave imaging and laser-interferometric methods will be applied more extensively. These techniques may not display the desirable resolution for detailed flaw characterization, but they often do provide a clear indication of a flaw. It is conceivable that a full field technique would be used for detection, and a point technique for subsequent characterization.

There is world-wide research activity in the general area of quantitative non-destructive evaluation. Many of the most recent results are annually presented at the Review of Progress in Quantitative Nondestructive Evaluation, and published in the Proceedings, Thompson and Chimenti, eds., (e.g. 1998 and preceding years). Detailed surveys of the techniques can be found in Handbooks, see e.g. ASM International (1989) and Bray and McBride (1992) and in books on the subject, see Bray and Stanley (1989) and Krautkrämer (1990). A number of technical journals are specifically devoted to publishing papers on non-destructive inspection and evaluation. The ones published in the English language are: Materials Evaluation, Journal of Nondestructive Evaluation, Research in Nondestructive Evaluation and NDT&E International.

In recent years some of the most interesting results have been in the following general areas:

measurement models
probability of detection studies
data processing
coupling to artificial intelligence methodology
retirement for cause procedures

as well as in specific techniques such as

self-compensating methods
imaging techniques
self-focusing methods
laser-based ultrasonics
resonant ultrasonic spectroscopy
EMAT-based ultrasonics
acoustic microscopy
X-ray backscattering
SQUID technology
thermal-wave imaging
pulsed eddy currents
applications of electromagnetic waves
laser interferometric techniques
integrated microsensors

or for specific applications such as

crack detection
adhesive bond testing
corrosion detection
materials characterization

In this paper, results quite closely related to solid mechanics, primarily in quantitative ultrasonics will be described.

3. Measurement models

It has now become well recognized that a fundamental approach to NDE must be based on quantitative models of the measurement processes of the various inspection techniques. A model's principal purpose is to predict, from first principles, the measurement system's response to specific anomalies in a given material or structure, (e.g. cracks, voids, distributed damage, corrosion, deviations in material properties from specification, and others). Thus, a measurement model includes the configuration of probe and component being inspected, as well as a description of the generation, propagation and reception of the interrogating energy. In the ultrasonic case this description requires computations of the transducer radiation pattern, refraction of the beam at the parts' surface, the beam profile and the propagation characteristics in the host material including effects of material anisotropy, inhomogeneity, attenuation, diffraction losses, etc. Detailed modeling of the field–flaw interactions which generate the measurement system's response function are also included, as well as information of material and other conditions that produce noise and add an uncertainty to the measurement results. A well constructed measurement model should be able to predict specific instrumental responses to anomalies in complex materials and structures as well as to 'standard' flaws placed in various calibration blocks.

A number of measurement models have been formulated in the past several years for different inspection techniques. For practical applications, the challenge lies in making approximations that permit the computations to be tractable while retaining sufficient accuracy so that the engineering applications are not compromised. Measurement models for ultrasonics have been discussed by Achenbach (1992), and more recently by Schmerr (1998).

The availability of a measurement model has many benefits. Numerical results based on a reliable model are very helpful in the design and optimization of efficient testing configurations. A good model is also indispensable in the interpretation of experimental data and the recognition of characteristic signal features. The relative ease of parametrical studies based on a measurement model facilitates an assessment of the probability of detection of anomalies. A measurement model is a virtual requirement for the development of an inverse technique based on quantitative data. Last, but not least, a measurement model whose accuracy has been tested by comparison with experimental data provides a practical way of generating a training set for a neural network or a knowledge base for an expert system.

4. Probability of detection

The implementation of a measurement model should be coupled to the probability of detection (POD) concept. This is a representation of the probability that a given measurement system will be able to detect a specific flaw (when it is larger than a specified size) in a given material/structure. It incorporates knowledge of the signal detected by the measurement system together with statistical information concerning flaw distributions and instrumental noise/thresholding levels. A POD curve shows the probability of a flaw's detection as a function of flaw size for a specific inspection technique. For an ideal technique, the POD of flaws smaller than a critical size (as determined by performance requirements and material properties) is zero whereas the POD for any flaw greater than this size is unity. In this case, there are neither false rejects of good parts nor false accepts of defective ones. However, POD's for real NDE Techniques are never as sharp and as discriminatory as indicated by the ideal curve, with the result that there are regions of uncertainty with false rejects and false accepts. If the probability of failure (PF) of a structure as a function of time has been established, inspections with a known POD justify a downward adjustment of the PF subsequent to a successful inspection.

Until recently, essentially all applications of the POD concept have been empirical, i.e., a statistically significant number of samples are prepared with artificial flaws and then experiments are made by a number of operators to test the NDE technique. This usually is a slow and expensive process that includes variable operator performance in its answers. With the advent of measurement models, however, the POD can be calculated for a specific set of conditions and verified with a few experimental samples at a considerable cost saving and with a capability for predictable extension to other inspection conditions. For example, signals that can be calculated from the various measurement models can be inserted into the POD integrals and the POD can then be calculated for specified flaw and measurement system conditions. This calculation then provides a useful measure of the systems predicted response that is independent of the operator's capabilities, see Thompson (1999) and Meeker et al. (1998).

5. Some new tricks and techniques of ultrasonics

Ultrasonic techniques remain the workhorses of nondestructive inspection. Ultrasound, defined as sound inaudible to the human ear, i.e., with frequencies above about 20,000 Hz, requires relatively simple equipment for generation and detection. Hence, it is used extensively, using piezoelectric transducers, with water coupling in an immersion tank, or for direct contact with contact transducers.

A recurring problem with contact transducers is the quality of the thin coupling layer between the transducer and the structure. This layer generally is water, oil or some kind of grease. The thickness and homogeneity of coupling layers is difficult, if not impossible, to control, particularly if the transducers have to be moved during the testing procedure to optimize the position for signal reception. A method to eliminate the effect of the coupling layer, known as the self-compensating or self-calibrating technique was proposed by Achenbach et al. (1992). The method uses two transducers, and combines the measured voltages in such a way that the effect of the coupling layers is eliminated and the measurement is directly related to the physical parameters that are of interest.

Many applications of ultrasonics are done using water coupling in an immersion tank. The effectiveness of that technique for flaw detection and characterization can be greatly enhanced by a capability to focus the ultrasound. A conventional ultrasonic focused transducer is, however, rather inflexible in that its direction of ultrasound radiation and its focal length are fixed. Direct focusing on a flaw is, therefore, often not possible without a great deal of scanning. Greater flexibility can be obtained by the use of a time-delay steered array which can generate a focal spot in the acoustic beam at a specified beam angle. A significant further improvement can be obtained by the use of an adaptive technique that automatically focuses the beam on the flaw that produces the largest scattered signal in a dispersed cluster of flaws.

A time-delay steered array consists of a set of transducers placed in a geometrical pattern, with the capability of exciting the individual transducer elements in a predetermined time sequence. Appropriate delays in the excitation of individual elements in the array result in the generation of a focal spot in the acoustic beam transmitted from the array at a particular beam angle. The manipulation of these time delays to beam steer throughout a large component is performed by electronic means, which results in faster imaging than by conventional mechanical methods. It is possible from geometric considerations to calculate the delay necessary to focus at a particular location if the velocity of sound is known. Furthermore, for an array which is operated as a single receiver i.e., when the signals received by the individual elements are superimposed to generate a single array output, this output can be improved significantly by correcting the individual signals for the differences in arrival times. The two time compensating methods are called sonification and reception focusing, respectively.

There are, however, clearly problems with a time-delay steered array when it comes to detection and characterization of discrete defects. In the first place, the location of the defect is unknown, secondly, any material variations can cause the focal point to be not well defined or at a different depth than calculated, and thirdly, the corrections of the arrival times of the received signals may contain errors that will produce phase aberrations and thereby reduce the effectiveness of the array.

Schemes have been proposed to enhance the flexibility of an array and to improve its output. A time delay correction technique for reception focusing was presented by Flax and O'Donnell (1988). Their method assumes that the magnitude of sound velocity inhomgeneities in the propagating medium is small enough that phase distortion is negligible. A cross-correction algorithm is used to estimate the time delay between signals arriving at neighboring elements and these delays are then compensated for to focus the received signal. Flax and O'Donnell (1988) report that their phase aberration correction technique performs almost perfectly with a scatterer that acts like a single point source. The point target produces spherical waves that have a slight phase aberration due to the propagating medium. The single point source case is, however, only an approximation for most applications. Typically, a region of interest will contain many randomly scattered passive sources with no single scatterer being dominant. They also proposed an iterative method for correction slight phase aberrations in a region with random scatterers with no dominant scatterer. This method has been shown to yield good results after only four iterations.

Adaptive time-delay focusing is not the most general scheme for focusing through an inhomgeneous material. Fink (1992) has proposed a general method employing a time-reversal mirror (TRM). In this process, the pressure field from a scatterer is sampled and recorded. Then, the field is time-reversed and re-emitted. Whereas the adaptive time-delay method employs standard pulser/receivers for each transducer element, the time reversal method requires a programmable transmitter capable of synthesizing the time-reversed version of the received signal for each element. Unlike the adaptive time delay technique, the TRM focusing method can compensate for distortions due to a correlated effect which could be produced by an inhomogeneous medium. However, the expense of the necessary electronics makes the TRM method suitable only for those NDE applications that justify the cost and complexity.

Beardsley et al. (1995) have proposed an in-between course. The cross-correction technique of Flax and O'Donnell (1988) is used to determine time delays of reception of the largest amplitude signal at the elements of the array. Next, the original transducer signal is re-emitted with the appropriate time delays, rather than time-reversing the complete received field *à la* Fink (1992). This procedure serves to focus acoustic energy on the scattering source, i.e., it produces sonification self focusing. Where multiple scattering sources are present, the technique will focus the transducer on the strongest scatterer if the adaptive technique is applied iteratively. Once good signals are being received, the cross-correction technique may be applied once again on the largest signals arriving at neighboring elements to achieve reception focusing, as discussed above. The technique has been extended to surface waves and Lamb waves, see Deutsch et al. (1997).

Methods of generating ultrasound in a non-contact manner are of increasing interest. The best-known of these techniques are air-coupled transducers, electro-magnetic acoustic transducers (EMAT's) and

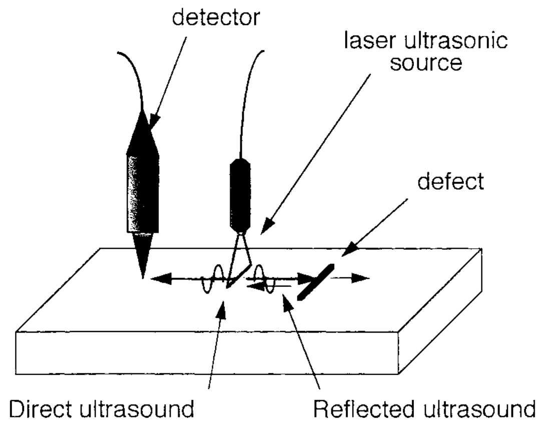

Fig. 1. General configuration of LBU system.

laser-based ultrasonics. Air coupled transducers suffer from a relatively low efficiency due to the large differences of the mechanical impedances of air and materials of components that are to be inspected. They are beginning to find applications in the NDE of composite materials. EMAT's have severe restrictions on the applicable frequency range, and they require electrical conductivity of the object. The physical principles of measurements with EMAT transducers have been discussed in detail by Thompson (1990). An interesting new development is taking place in the area of surface microfabricated ultrasonic transducers, both for air and water transmission, see Ladabaum et al. (1998).

Laser-based ultrasonics (LBU), involves the generation of ultrasound by laser illumination and the detection of ultrasonic signals by laser interferometric techniques. LBU has many advantages for applications to quantitative nondestructive evaluation including non-contact generation and detection, remote placement of equipment using fiber-optics, easy scanning, absolute displacement calibration, both broad band and narrow band signal generation, wide frequency band measurement, and applicability to curved surfaces. A thorough discussion of the principles and techniques of laser-based ultrasonics has been given by Scruby and Drain (1990). Optical detection of ultrasound has been reviewed by Wagner (1990).

Laser generation of ultrasound and the detection of the ultrasonic waves using laser interferometry are areas of active research. In earlier papers, the present author and co-workers have discussed an LBU system which employs a diffraction grating for illumination of a line-array to generate narrow-band surface waves and Lamb waves, and a fiberized heterodyne dual-probe laser interferometer to measure the ultrasonic signals. Recent development include the use of optical fibers to remotely generate and detect ultrasound with the acoustic energy focused into a selected narrow frequency band, the generation system uses a binary diffraction grating to separate a signal laser beam into 10 equal but spatially separated laser beams which are focused into 10 individual fibers. Results have been obtained over a range of frequencies from 2.7 to 7.7 MHz.

A recent paper by Fomitchov et al. (1997) reports progress towards the development of a robust low cost fiberized Sagnac laser interferometer suitable for field applications. It presents a low noise system using a low cost, long coherence HeNe laser that has better intensity noise characteristics than typically used laser diodes. A scheme for elimination of parasitic interference utilizing a frequency shifting technique has been developed. The primary advantage of the Sagnac interferometer is that it is exactly path matched and as such requires no heterodyning or static path compensation for sensor stabilization. The Sagnac interferometer is suitable for the measurement of ultrasonic surface waves arising from laser- or PZT-generated sources or from acoustic emissions. The general configuration of a laser-based ultrasonics system is displayed in Fig. 1.

In recent years the technique of resonant ultrasound spectroscopy has found a number of important applications in nondestructive evaluation, see Migliori and Sarrao (1997).

6. Neural networks

Whatever sensor, data-collecting and data-processing methods are used, it is to be expected that the volume of the data will be large and that it will be difficult to discriminate between ultrasonic signals generated by flaws and harmless noise. As a consequence a human operator may not be effective in extracting relevant information for decision making purposes from an overwhelming flow of data. Neural networks can play a major role in the recognition of sets of data that are related to damage or failure phenomena in the component or structure that is being monitored.

Neural networks must, however, be applied in an intelligent manner. A brute force application of a neural network will require a very large set of training data (usually not available) and a large computer, and then might still not give very satisfactory results.

Specifically, a neural network with an analog output has been worked out to estimate the crack-depth from ultrasonic signals backscattered from a surface-breaking crack in an aluminum plate. The network has only one response unit and this unit directly reports the crack depth as an analog value from the measured signals. A completely synthetic data set, spot-checked by comparison with experimental results, has been utilized for the training of the network. The synthetic data set was obtained by solving the boundary integral equations that formulate the problem by the boundary element method. A Gaussian modulated sinusoid was utilized as an incident signal. Results have been presented by Takadoya et al. (1996). An extension to include fuzzy reasoning was presented by Ogi et al. (1996).

7. Integrated microsensors

An interesting new development in the sensing area brings together solid-state microsensors and advanced signal processing methods. The microsensors include acoustic emission (AE) sensors for the detection of crack nucleation and generation, microbeam accelerometers for the detection of unwanted mechanical vibrations and temperature sensors for both signal reference and identification of excessive heating. A goal of the work in this area is to realize inexpensive silicon chips, or 'coupons', which can potentially be distributed over critical regions of a structure. Such a coupon may contain a variety of microsensors for detections and cross-configuration of multiple defect signatures. In addition it may be possible to implement wireless communication between the sensors and a central location. By also integrating analog signal conditioning electronics, A/D converters, digital signal processing circuits, memory, and telemetry with silicon based microsensors, smart microsystems can be formed. The silicon-based concept has been discussed by Polla and Francis (1996). At the present time, the dimensions of the coupons are 1×1 cm.

8. Acoustic microscopy

An acoustic microscope consists of four main components: the acoustic probe, the pulse-mode measurement system for transmitting and receiving signals, the mechanical system for alignment and movement of the specimen and a computer for controlling the system and processing the recorded wave forms.

The acoustic microscope was originally developed as another way to do microscopic imaging. It has the advantage that subsurface artifacts in a solid body can be imaged. However, even for imaging of the surface, sometimes greater contrast can be achieved than with an optical microscope. The historical development of acoustic microscopy was discussed by Quate (1985). The physics and applications of acoustic microscopy have also been discussed by Briggs (1992). The imaging microscope uses a point-focused acoustic lens. A line focus lens which gave rise to the new area of quantitative acoustic microscopy was proposed and developed by Kushibiki and Chubachi (1987).

Line-focus acoustic microscopy (LFAM) provides a method to determine the elastic constants of homogeneous specimens and thin-film/substrate configurations. For thin films, these elastic constants very much depend on the details of the deposition technique. They are important to know, to understand and predict the mechanical behavior of thin films. The elastic constants are determined from the velocities of leaky acoustic waves that can be obtained from $V(z)$ measurements. For high frequency toneburst sonification of the specimen, the $V(z)$ curve is a record of the transducer output voltage V as a function of the distance z between the lens focal line and the specimen surface. Generally speaking, more than one elastic constant has to be determined, and hence more than one data point is required. Hence, for isotropic materials sufficient data cannot be procured with a single mode. By virtue of the line-focus lens, the velocity for anisotropic solids can be measured, as a function of the angle defining the propagation direction on the surface, to yield a sufficiently large set of data. The technique has been discussed in great detail in a recent review article by Achenbach et al. (1995), which also lists numerous references. For isotropic thin-film/substrate configurations, measurements at various frequencies or for different film thicknesses may be carried out to obtain sufficient data using standard measurement procedures. There are, however, obvious advantages to working with a single specimen and at a single frequency. This can be done by considering the contribution of more than one leaky wave mode to the $V(z)$ curve. $V(z)$ curves have also been simulated numerically using a measurement model with selected elastic constants. Both the experimental and the numerical $V(z)$ curves go through the same $V(z)$ analysis to yield their respective predictions for the leaky acoustic wave velocities. The determination of elastic constants is then achieved through minimization of the differences between the theoretical predictions and the experimental results by a numerical iterative searching procedure known as the simplex method.

Basic to the interpretation of $V(z)$ curves is a reliable measurement model. A $V(z)$ measurement model simulates the measurement procedure, including any systemic errors that may occur in the determination of the velocity from experimental $V(z)$ curves. For example, effects due to multiple modes, will be replicated in the numerical model. The material constants obtained from comparisons of results from the measurement model and experiments will, therefore, be free of these systemic errors. A measurement model for the $V(z)$ curve has been described in detail in the earlier cited paper by Achenbach et al. (1995).

Detailed results for measurements of surface acoustic wave velocities as functions of the angle defining the propagation direction over thin-film substrate configurations, and the use of these results to determine elastic constants, have been presented in the above cited review paper. Results for measurements made with the line focus acoustic microscope in conjunction with a multiple wave-mode method to determine elastic constants from a single $V(z)$ measurement have also been discussed. The use of multi-mode information improves the convergence of the method.

9. Crack scattering theory

A mathematical crack is a surface in a solid body that cannot transmit surface tractions. Under the influence of incident ultrasound, a crack may, therefore, become a surface of displacement discontinuity. The faces of a mathematical crack are infinitesimally close prior to ultrasonic excitation, and they are stipulated not to interact when the body has been excited. This is an acceptable approximation for a real crack if the faces do not touch when the solid is disturbed. The separation of the crack faces, the 'crack opening displacement', produces a reflection, or in more general terms a scattered field. A measurement of the scattered field provides information in the crack.

Let us consider the case that the probing ultrasound is generated by a contact transducer on a solid body. In this process a voltage is applied to the piezoelectric crystal in the transducer. The resulting deformation of the crystal presses against the body and produces ultrasound, which propagates into the body and is scattered by the crack. The scattered field, which may include a specular reflection is detected by the same transducer (pulse–echo), or by a second transducer (pitch–catch). In the detection process the scattered ultrasound deforms the detecting transducer, and this deformation produces a voltage which is measured. Thus, the probing field is defined by a single number, the value of the exciting voltage, while the scattered field produces only one other number, the value of the detecting voltage. The radiating transducer has, however, a finite dimension which produces a beam of ultrasound of a certain cross section, which interacts with a crack of a generally unknown size, shape and orientation, and the scattered field sonifies the cross-sectional area of the receiving transducer to produce a voltage. Somehow a measurement of the input and output voltages is expected to provide information on the rather complicated wave propagation and wave scattering process described above, and specifically on the geometrical details of the crack. Clearly a measurement model is required to connect the input and output voltages to the crack.

An important component of the measurement model is provided by the scattering matrix. The concept of a scattering matrix was transplanted from electromagnetic wave theory to elastodynamics by Auld (1979) and Kino (1978). Expressions for the scattering coefficients can be derived by the use of the Betti–Rayleigh reciprocal identity and two selected elastodynamic states of stress and deformation, see also Thompson and Gray (1983).

10. Materials characterization

As discussed in some detail by Thompson (1996), in many cases correlations have been noted between ultrasonic parameters, such as velocity, attenuation and backscattering, and material properties controlling the mechanical behavior. In general, the underlying reason for these correlations is that the same microstructural features that affect the ultrasonic measurement, such as grain size, grain boundaries, inclusions, porosity and dislocations, also play an important role in determining material properties of interest. However, there are generally multiple microstructural features which affect both the ultrasonic measurement and the material properties. Since the functional relationships are not the same, only empirical relationships under controlled conditions can be expected. For example, it has been attempted to establish a correlation between fracture toughness and a parameter associated with the attenuation of ultrasonic waves. Other attempts have been directed to quantifying the level of material degradation due to cyclic fatigue, hydrogen attack and irradiation embrittlement. The measurement of residual stress is another area of interest to the prediction of the performance of structures. There has been considerable effort devoted to the development of ultrasonic tests for these purposes. For a more detailed discussion we refer to the paper by Thompson (1996).

In the present context we should also mention the large body of work that has been devoted to measuring the effective elastic constants of composite materials by ultrasonic techniques. Numerous references can be found in Thompson and Chimenti (1998) (and preceding years).

11. Intelligent processing of materials

Applications of QNDE to intelligent processing of advanced materials are closely related to techniques for materials characterization discussed in the preceding section. Advanced materials can provide specialized properties or combinations of properties. Complicated processing operations are, however, generally required to achieve the unique microstructures and the related special properties. Because the relationships among the processing parameters, the microstructure and the resulting material properties and performance are often not fully understood, and because the microstructure may be difficult to control, reproducibility in these materials is often unsatisfactory. Intelligent processing, i.e., a computer-based approach to control the evolution of microstructure is the method of choice for overcoming these difficulties.

Intelligent processing utilizes NDE sensors such as ultrasonic transducers, lasers, optical fibers and temperature probes to measure, in real time, parameters which characterize the microstructure or variables which define the state of sintering or solidification. These real time data from NDE-type sensors plus data from conventional process variable sensors are transmitted to a computerized decision maker which may adjust the processing of the material, based on sensor data and a process model.

12. Relevant research in elastodynamics

Solutions to elastodynamic problems form the basis for ultrasonic measurement models. Numerous relevant papers are dispersed in the acoustics, the solid mechanics and the applied mathematics literature. Of interest are wave propagation solutions for various kinds of source distributions in diverse media, such as anisotropic and inhomgeneous materials. Reflection and transmission at boundaries and interfaces are also of obvious interest. An important category are solutions for scattering of elastic waves by cracks, cavities and inclusions. Except for very simple geometrical configurations such problems can generally not be solved in closed form. A class of approximations is provided by ray theory. In a rigorous approach the formulation of a scattering problem can be reduced to an integral equation over the surface of the scatterer, in terms of a Green's function and the field on the scatterer. Once this integral equation has been solved, the field elsewhere can be expressed in terms of a corresponding integral representation. Unfortunately the integral equation can generally not be solved analytically, but requires a numerical technique such as the boundary element method. Alternatively the field on the scatterer can be approximated, but such approximations generally have validity only at low or high frequencies. Other numerical techniques, such as the finite element and finite difference methods have found applications for some cases.

Other problems that are of interest for QNDE applications concern wave propagation in layers and in multilayered configurations.

13. Probabilistic fatigue methods

Fracture mechanics is the fundamental discipline underlying failure analysis and life prediction based on the presence of cracks. Given the fracture toughness of the material and the load sustained by the component, fracture mechanics enables an engineer to calculate the critical size of a crack at a given location. A component is judged to be safe if the crack is smaller than a critical size and is not expected to grow to a critical size prior to the next inspection. Cracks which are judged acceptable may still grow, but at a rate which in principle is predictable. This leads to the 'damage tolerant' philosophy: a component containing a macroscopic crack or flaw is acceptable if it can be shown that at the predicted stress levels, the flaw has almost zero probability of growing to critical size prior to the next inspection.

The underlying concept in developing accept/reject criteria for a component is based on detecting and characterizing a defect and evaluating it in terms of fracture mechanics and a fatigue crack growth law. The aim is to determine whether a crack in a structure is sufficiently small so that failure can be precluded with a high degree of certainty.

Probabilistic fatigue methods are often applied when critical structural components are subjected to non-destructive evaluation (NDE) techniques, so that cracked components can be identified and repaired or replaced. These inspections can significantly reduce the probability of fatigue failure of structures. Quantified measures of reliability (provided by probabilistic methods) allow maximization of inspection benefits through optimization of the inspection schedule. They also allow comparison of the effectiveness of various inspection methods.

A risk analysis methodology for the assessment of structural integrity of aircraft structures has been outlined by Berens et al. (1991). This methodology, which is based on the direct integration of the probability of failure, works well when the number of random variables is relatively small and a single parameter characterization of crack size is adequate. However, when it is desirable to characterize crack growth in detail, other modeling techniques such as Monte Carlo simulations (MCS) and the first order reliability method (FORM) are needed for calculating probabilities of failure. In an alternative approach the first order reliability method is augmented to account for the effects of the inspections so that the crack size distribution need only be characterized at an initial state.

The fatigue reliability problem is outlined in some detail by Achenbach et al. (1997). The role of NDE inspections, which enters through the probability of detection (POD) curve, is illustrated. A numerical example is given to explore the influence of POD on fatigue reliability.

14. Recommended approach

Condition monitoring can contribute to structural reliability in a very important manner. The techniques for condition monitoring belong in the general area of quantitative non-destructive evaluation. The associated reliability analysis uses established techniques of failure prediction and reliability assessment.

A program in the general area of condition monitoring for Structural Reliability should have the following components:

1. *QNDE*: Sensors and Techniques (smallest detectable flaw, POD), Measurement Models, Imaging Methods, Neural Networks, Flaw Characterization.
2. *Structural Reliability*: Critical Failure Mechanisms, Nucleation of Flaws (to determine the need for a first inspection), Flaw Growth Rates (for frequency of inspection), Reliability Analysis.

The application of QNDE techniques can be either on a fixed inspection interval basis, or it can be as a continuous process. The continuous monitoring approach is generally achieved with permanently installed sensors, which sound an alarm when an undesirable defect situation is reached. Structures that can be monitored this way are considered to belong to the general category of smart structures.

In QNDE, a combined theoretical/experimental approach is recommended. In the theoretical work measurement models should be developed for the measurement processes of the ultrasonic inspection techniques. These models can be used in the design of inspection procedures and in the interpretation of the data. Immersion transducers, contact transducers and laser-based ultrasonics may be used for the inspection. The observed damage should be related to strength considerations by the use of fracture mechanics.

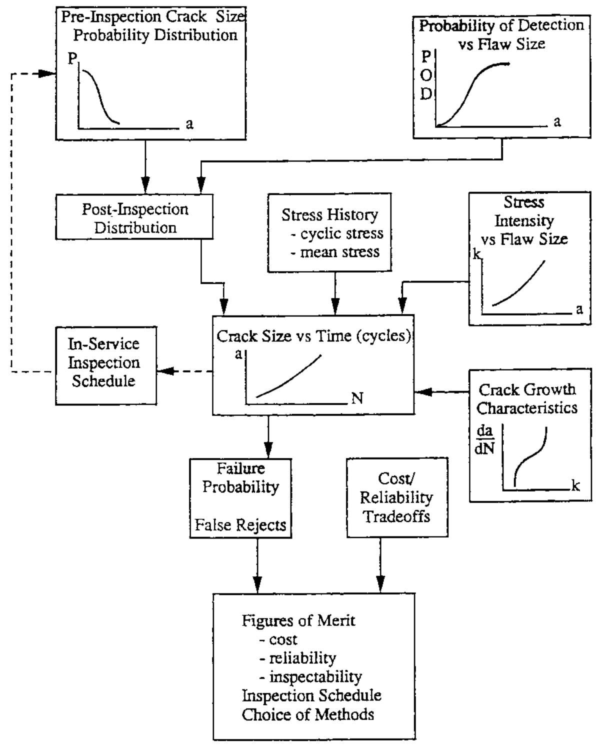

Fig. 2. General methodology of QNDE and reliability assessment for metal parts under cyclic loading.

The methodology should be based upon the complementary and integrated roles of quantitative non-destructive evaluation and reliability assessment via life-cycle prediction.

This systematic approach to quantitative non-destructive evaluation for a metallic structural component containing a crack is illustrated in Fig. 2. As can be seen from the figure, the underlying concept in developing accept/reject criteria for a component is based on detecting and characterizing a defect and evaluating it in terms of fracture mechanics and a fatigue crack growth law. The aim is to determine whether a crack in a structure will be sufficiently small so that failure can be precluded with a high degree of certainty.

In addition to the QNDE for discrete flaws discussed above, work is needed in the development of new sensors and related techniques for the evaluation of material properties and for processing methods. In the processing area new sensors and measuring techniques have to be integrated with process models.

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