Non-destructive Testing

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Preface

The industrial use of non-destructive testing (NDT) greatly expanded during World War II, although some of the techniques were known and used on a limited scale long before that time. It has attracted specialists, even specialists in one particular NDT method with only a limited knowledge in other fields of NDT, and this book has been planned to give concise coverage of the major fields of NDT and to indicate how they overlap.

It is written for engineers at undergraduate and graduate levels, to give an understanding of the physical principles, capabilities and limitations of a wide range of NDT methods, including the latest developments, so that the most appropriate techniques can be chosen for a specific application.

There is insufficient space in a book of this size to cover any NDT method exhaustively and an attempt has been made to provide a balance between the relative importance of the various methods.

Non-destructive testing is one part of quality control and therefore forms a link between the designer, the production engineer and the quality-control department. Personnel in all three groups need to understand NDT and it is hoped that this book will meet this requirement.

I wish to thank friends and colleagues engaged in NDT in several countries for the opportunities I have been given for technical discussion on points of detail in the text, in particular Mr C A Hunt, my former colleague at RARDE.

I should also like to thank my wife for her continuous support, for her assistance in typing the text, proof reading and for her helpful criticisms of my phrasing.

R Halmshaw

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Introduction

Non-destructive testing (NDT) has no clearly defined boundaries. A simple technique such as visual inspection is a form of non-destructive testing, as also might be the measurement of an obscure physical property such as Barkhausen noise. It used to be considered that there were five major methods—radiographic, ultrasonic, magnetic, electrical, and penetrant—but all these can be subdivided, and to them must be added a range of important new techniques such as acoustic emission methods, thermography, and holography. Further, a large number of even more specialised methods have been investigated and found to have applications in particular limited fields: these are methods such as proton annihilation, neutron scattering, proton radiography, microwaves, and nuclear magnetic resonance. In a book of this size it is not possible to describe in detail all the range of possible NDT methods.

Many NDT methods have reached the stage of development where they can be used by a semi-skilled operator following detailed procedural instructions, with safeguards built into the equipment. The advent of microcomputers allows procedures to be pre-programmed and cross-checked, so that a competent operator does not necessarily need to understand all the physics of the technique being used. However, it is desirable that the supervisors of the inspection, the designers who specify the techniques to be used in terms of their performance and attainable sensitivity, and the development engineers working on new methods, do have a thorough scientific understanding of the fundamental physics involved.

This book therefore is aimed at the undergraduate and graduate engineer, designer, or metallurgist, who needs to understand the basis of a wide range of NDT methods, so that the most appropriate one for a specific application can be selected. One of the problems in NDT is that there is often too large a choice of methods and techniques, with too little information, except sales literature, on the performance of each in terms of defect sensitivity, capital cost, speed of operation, running costs, or overall reliability. Some NDT methods have been much over-sold in recent years.

In this book, the amount of mathematics included has deliberately been kept to a minimum, partly so as not to burden the reader unnecessarily, and partly because although the mathematical principles of such topics as wave propagation or radiation scattering might be satisfying to an academic reader, they do not always add to the practice of NDT, nor do they necessarily point the way to future development.

There are, however, rapid advances being made in the computer-modelling of electrical, magnetic, and radiation fields, which appear to have very considerable potential in realistically representing the conditions met in practical specimens: where there has been useful progress, these methods have been mentioned in the appropriate chapters. At the end of each chapter, a list of further reading is included.

The terms 'non-destructive testing, NDT,' and 'non-destructive inspection, NDI,' are taken to be interchangeable, but a newer term 'non-destructive evaluation, NDE,' is coming into use. In NDT or NDI, in flaw-detection applications, the end product is taken to be a description of the flaws which have been detected—their nature, size, and location. From this, either in conjunction with a standard for acceptable/rejectable flaws, or a knowledge of, for example, fracture mechanics, a decision is then made on the serviceability of the tested item. This decision is made by the designer, but in practice may be left to the NDT personnel, or the NDT inspector. In NDE, it is assumed that this acceptance/rejection of flaws is part of the non-destructive testing process.

There are only a few NDT applications, such as the testing of nodular cast iron, in which a direct relationship can be found between the NDT measurement and the strength of the material. With the development of data analysis by computer, however, together with pattern-recognition methods, it may soon be possible to analyse NDT data directly, in terms of component acceptability, so that the equipment can be programmed to produce (Go/No-go) decisions. These methods should therefore be described as NDE rather than NDT.

The terms 'flaw' and 'defect' have been used interchangeably and neither has been taken to signify either an acceptable or an unacceptable condition. More neutral terms such as 'discontinuity', 'imperfection', or 'inhomogeneity' are too cumbersome for general use, and the terms 'flaw sensitivity' and 'defect detectability' are so widespread in NDT, and have been used for so many years, that it seems unnecessary to propose anything different. It is understood, however, that for legal purposes the EEC has ruled that the term 'defect' signifies that the material, fabrication, etc., is defective, i.e. unserviceable. The term 'flaw' should therefore be used for any imperfections which are not considered to be rejectable. Thus, on this interpretation of the words, there is no such thing as an 'acceptable defect'.

The general topic of the determination of unacceptable defect sizes has been taken to be outside the scope of this book, as has the more general topic of quality control, of which NDT is obviously one part, but a short chapter is included on acceptance codes.

Although a great deal of non-destructive testing is carried out for flaw detection in materials—e.g. the detection of weld defects, lack of bond in adhesive joints, and fatigue cracks developing during service—it should not be forgotten that NDT has important applications in the examination of assemblies, to detect mis-assembled components, missing or displaced parts, to measure spacings, etc. In many of these applications, it is possible to be quite specific on what it is necessary to detect (i.e. the required flaw sensitivity), or what accuracy of measurement is needed, and devise an NDT technique suitable for the particular application which may often be much faster or cheaper than a more conventional technique. Examples of this type are ordnance inspection (fuzes, etc.) for correction of assembly, aero-jet-engine inspection during test running to measure blade spacings during speed changes, ultrasonic thickness gauging, and metal alloy sorting.

There is a new factor coming into NDT, which seems likely to bring major modifications to most NDT methods. This is the use of computer techniques, using small computers. Apart from the obvious, rather trivial uses to simplify calculations, it is now possible to collect, store and process vast quantities of digital data at very high speeds. For example, in ultrasonic testing, in the signals produced by a transducer from a flaw there is a mass of data which is not used in conventional ultrasonic flaw detection. This can all be taken into a data store, and computer programs devised to extract information such as spectral composition, rise-time, pulse length, and maximum amplitude. At the moment it is not even certain, in some applications, what are the relevant properties of the signals which are needed. In addition, the computer can be used to choose the technique parameters for a given application, to adjust the equipment accordingly, and to provide warning if there are deviations, or a change in monitoring signals.

On NDT methods which provide an image, it is very likely that computers will be applied with pattern-recognition programs to interpret automatically the results of NDT. Perhaps a word of caution might be interjected here: the human eye is a very powerful and versatile instrument, when used with a trained memory, particularly in terms of pattern recognition against a noisy background, and the physics of imaging suggests that it might not be too easy to replace the eye with a computer. Against this, of course (computer) digital image enhancement techniques are already being used in a number of applications, particularly for signal-to-noise enhancement.

Returning to materials inspection, it has become fashionable in recent years to divide defect evaluation methods into quality-control criteria and fitness-for-purpose criteria. For the latter, acceptance standards must be defined on a case-by-case basis, usually using fracture mechanics. For the quality-control criteria, the requirements are based on a more general engineering experience, and the inspection is directed towards detecting the most common manufacturing defects, with an implication of less-severe NDT requirements. These concepts again emphasise the need, not always fully documented, of having a knowledge of the defect sensitivities required, in detail, before applying NDT.

Regarding the comparison and evaluation of NDT methods, there have been several published papers purporting to compare the performance of different NDT techniques and methods. Nearly all these reports have taken a particular type of defect or specimen, collected or fabricated a set of specimens with different sizes or severities of the defect, inspected them non-destructively, and then analysed the results statistically. Few of these trials have contained enough specimens to be statistically significant when there may be problems of reliability and measurement accuracy as well as defect detectability. More importantly, the results obtained, although valuable, depend almost entirely on the nature of the particular defect used. Thus, in a trial involving small fatigue cracks at section-changes on a light-alloy panel, it is not surprising that eddy current and penetrant testing were superior to ultrasonic testing and radiography. On corroded surfaces, penetrant inspection was found to be inferior to the eddy current technique, in reliability if not in sensitivity. A comparison of ultrasonic and radiographic methods will produce very different conclusions if the defect chosen is porosity rather than cracks.

The use of a minimum detectable defect size in any specific application is not an efficient assessment of either a technique or an operator. Probabilities and confidence levels are also needed, and laboratory trials cannot necessarily be extrapolated to field results. Most NDT techniques have a wide range of applications and comparison data is valid only for a particular application, a specific type of defect, and a particular material.

SI units have been used throughout the text, except where US Standards are quoted. Many of these still use inches, and in these cases the original American wording has been retained. If a standard asks for a $\frac{1}{16}''$ hole, it seems unnecessarily pedantic to convert this to 1.588 mm. Micrometres (μm) has been used in preference to microns, and 'mils' has not been used.

2
Visual methods

2.1 Introduction

Visual methods of surface examination, with or without optical aids, tend to be neglected by NDT personnel. Many of the most serious defects, from the strength point of view, are surface breaking, and while the detection of these can be enhanced by magnetic particle inspection, they can also often be seen by careful direct visual inspection. Such weld defects as severe undercutting, or an incompletely-filled groove, can be easily seen if the surface is accessible, and can lead to immediate rejection or rectification without the need for more expensive testing by ultrasonic methods or by radiography. In addition, surface shapes (contour gauging, profile gauging) and surface roughness provide valuable quality-control information. On a microscopic scale, the preparation of a local area of a specimen together with metallographic examination at various magnifications is a combination of destructive and non-destructive inspection, but often the amount of metal removed in preparing a local area of surface for examination is not sufficient to affect the subsequent serviceability of the component. In addition, surface replicas can be obtained both for macroscopic and microscopic examination. Finally, high-speed surface inspection, with automated output, is in itself a non-destructive inspection method for such products as bright steel sheet (see Section 2.5).

2.2 Optical aids

Aids to visual inspection should be used whenever practicable. For local examination of a portion of a metal which is directly accessible, a small hand lens, used in conjunction with a portable light such as a pen-torch, is very useful. A magnification of $\times 2 - \times 4$ is all that is usually required.

Industrial telescopes, usually known as borescopes, or introscopes, enable surfaces inaccessible to the naked eye to be seen. They are best known for examining the internal surfaces of tubes and piping, and for inserting into access holes in machinery. An important application is to the inspection of the surface of turbine blades in an aero-engine for cracking and corrosion, without a dismantling requirement.

The design of borescopes has been transformed in recent years by the application of optical-fibre techniques. These can illuminate a surface and retrieve the image over distances up to several metres. The desirable properties of a borescope are that it has as large a field of vision as possible, minimum image distortion, and adequate illumination. Borescopes are now available which are coupled to a closed-circuit television camera, and as an alternative technique, sub-miniature television cameras have been built for direct insertion into small pipework. If a television camera is used, the image can be taped, or disc-recorded. A further variant is to insert a small film camera into the structure and by remote positioning and operation, photograph the relevant areas directly on film. This has been carried out in radioactive environments in a nuclear power plant, by using film which is highly sensitive to light, but which is not overexposed by the background ionising radiation during positioning and exposure.

In all these remote viewing systems, the two main problems are:

(1) the effect of the direction of the illuminating light—if possible, this should be capable of being varied so that detail can be seen in relief, and glare and dazzle effects eliminated,
(2) identification of the precise area being seen.

2.3 In-situ metallography

This is not widely used, perhaps because of a lack of awareness of its potential value. A local area can be ground, polished, and etched. Electrochemical etching is easily done, in situ, even on a vertical surface, using a glass tube and a sealant to the surface. A portable microscope with a camera attachment is then used on the prepared area. Alternatively, a replication method can be used with cellulose acetate films moistened with acetone and spread on the etched surface. When dry, these films are peeled off and held between glass strips: they are examined with a reflecting aluminium foil background.

An alternative method of producing a replica is to use a varnish having a nitro-cellulose or plastic base, spread on with a spatula, and allowed to dry. Great care is needed in lifting the replicas off the surface. Instead of the aluminium foil background for viewing, the surface of the replica not containing the impression can be made reflecting by vacuum deposition of an aluminium coating.

Often a study of the surface microstructure of a material, in situ, can provide additional information to supplement other NDT findings.

2.4 Optical holographic methods

The advent of lasers and the science of coherent optics has led to a whole new range of optical inspection techniques, which come broadly under the heading of visual inspection. In addition, the ability to collect an optical signal with a television camera, digitise and store the data, and then subject the data to digital image processing, has further extended these techniques.

A group of techniques under the general heading of optical holography can be used for the comparison of specimens, or the measurement of small amounts of deformation under stress, or a study of the surface during vibration. As the presence of a defect is likely to cause changes in the deformation or vibration pattern, the methods can, by extension, be used for defect detection.

2.4.1 Principles of holography

The different parts of an object scatter incident light, producing light waves which have a certain amplitude and relative phase. Normal image storage systems, such as photographic film, respond only to intensity, i.e. to $(\text{amplitude})^2$, but there is much more information in the image and the holographic process allows use of the phase information, in addition to amplitude. This is achieved by producing interference between the waves from the object and a simple reference wave (Fig. 2.1(a)). The two waves, one having a complex distribution of phase and amplitude due to scatter on the specimen, and the other a uniform distribution, interfere to produce a pattern of dark and light fringes, which are recorded on a photographic plate (P), as a hologram. After photographic processing, the image can be reconstructed from the hologram by illuminating it, as shown in Fig. 2.1(b). The pattern on the hologram now acts like a complex diffraction grating, and an observer looking through the hologram plate sees the original object in place, even though it has been removed. The image is a virtual one, but is three-dimensional, and if the observer moves his head sideways, there is a full effect of perspective and depth. If this image is reconstructed with the object in its original position, the three-dimensional image superimposes exactly on the object, but if the object has moved slightly, or has been deformed locally, the observer sees bands of interference fringes on the surface, the number and spacing depending on the amount of object movement.

The following fundamental points about optical holography should be made.

(1) The light source must have suitable coherency properties, which in practice means laser light. A typical He–Ne gas laser has a useful temporal coherence length of about 20 cm.

(2) Very stable conditions are necessary during exposure-time. The relative motion between the object and photographic plate should be less than $\lambda/4$, where λ is the wavelength.

(3) If the angle between the reference beam ray and any one scattered ray from the object is β, then the fringe spacing, δ, is given by

$$\delta = \lambda/\sin\beta$$

so for $\beta = 30^\circ$, $\delta = 2\lambda \simeq 1\ \mu\text{m}$, assuming light of $\lambda \simeq 0.5\ \mu\text{m}$.

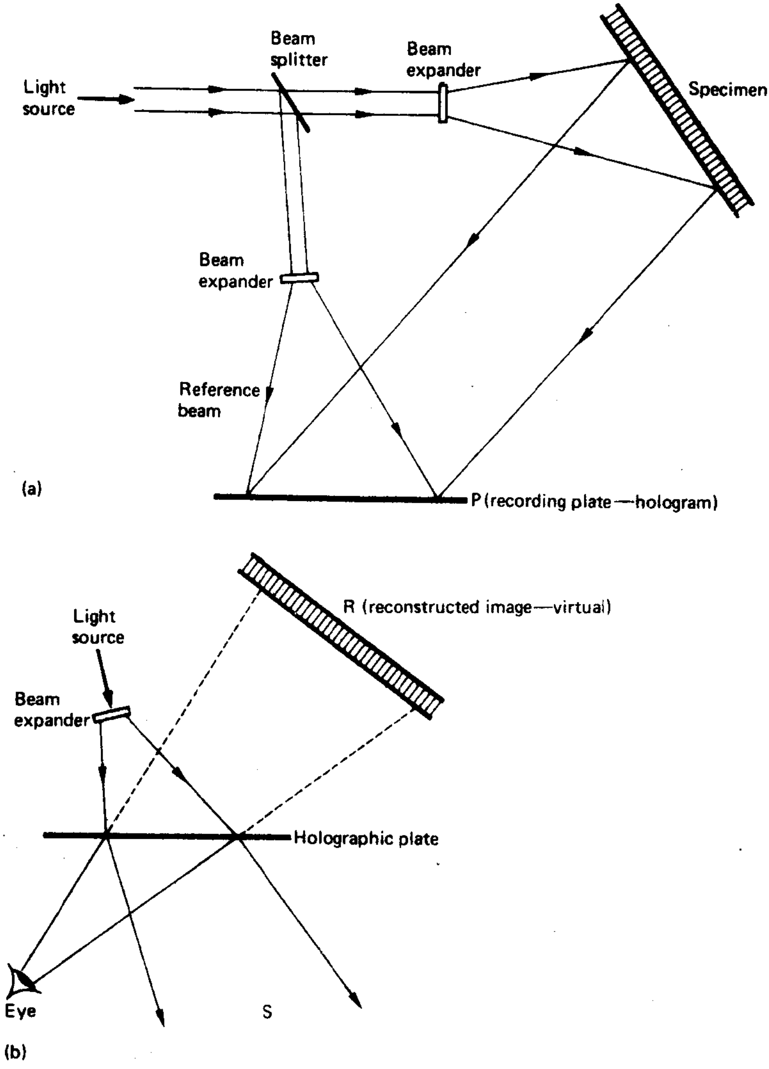

Fig. 2.1 Optical holography: (a) hologram formation and (b) image reconstruction

Thus the photographic emulsion must have a very high resolution if there is to be a useful field of view. A resolution of 1000 lines per mm is desirable, and this in turn requires a very high light intensity to maintain reasonable exposure-times.

The mechanism of image formation in holography can be described as follows. Considering a cross-section of the holographic plate (to simplify the equations to a one-dimensional case), if at position (x) on the holographic plate, the resultant wave from all points on the object has amplitude a_x and phase $\phi(x)$, it can be represented by

$$a_x \exp[-\mathrm{i}\phi(x)]$$

The reference beam can be considered as a plane wave of unit amplitude falling on to the plate at an angle α, and can be represented by

$$\exp(-\mathrm{i}kx)$$

where k is related to α and λ by $k = (2\pi/\lambda)x \sin \alpha$. The total amplitude, A_x, reaching the holographic plate at x will then be

$$A_x = a_x \exp[-\mathrm{i}\phi(x)] + \exp(-\mathrm{i}kx)$$

The intensity, I_x, is obtained by multiplying A_x by its complex conjugate. If it is assumed that the transmitted amplitude, A_t, through the photographic plate is proportional to the light falling on it,

$$A_t = BI_x$$

where B is a constant, when the reference beam of amplitude $\exp(-\mathrm{i}kx)$ illuminates the hologram, the transmitted amplitude will be

$$A_r = A_t \exp(-\mathrm{i}kx) = BI_x \exp(-\mathrm{i}kx)$$

or

$$A_r = B\{(1 + a_x^2) \exp(-\mathrm{i}kx) + a_x \exp[-\mathrm{i}\phi(x)] + a_x^* \exp[\mathrm{i}\phi(x) - 2\mathrm{i}kx]\}$$

The first term represents the light that passes straight through the hologram and the second term is the reconstructed wave, identical to the object wave in all but absolute amplitude (R in Fig. 2.1(b)). The third term corresponds to the first-order diffracted wave on the other side to the straight-through direction (at S in Fig. 2.1(b)). This is the conjugate wave and in some conditions can produce a real image.

By taking a hologram of a stationary surface, replacing the plate in its original position so that the holographic image is superimposed on the object, and then observing the moving fringes produced when the object is vibrating, there is effectively a 'live fringe' effect. The motion can be arrested by using pulsed illuminating beams at the reconstruction stage and pulsing these at the same frequency as the vibration. If the pulse-time is kept short, high contrast fringes can be seen, even at high orders of interference.

For defect detection in solid specimens, by deformation, a useful rule-of-thumb for holographic testing is that the defect should be at least twice as large in diameter as it is deep, or that a crack should be longer than the material thickness. While three-dimensional holographic images can be very impressive and also useful, for example in displays of museum specimens, the main use in NDT is to detect minute deformations, by holographic interferometry.

One technique is to expose the holographic plate for half the required exposure-time, and then apply a small strain to the specimen, mechanically or by heating, for the other half of the exposure. In this method of double-exposure holographic interferometry, let the amplitude of the initial wave at position (x, y) on the holographic plate be $U_1(x, y)$, and that of the second wave after a small object movement be $U_2(x, y)$, where

$$U_1(x, y) = a(x, y)\exp[-i\phi(x, y)]$$

and $$U_2(x, y) = a(x, y)\exp\{-i[\phi(x, y) + \Delta\phi(x, y)]\}$$

a being a constant and $\phi(x, y)$ the phase component at (x, y). Then dropping the (x, y) for simplicity of notation, the resulting intensity, I, from addition of the waves is

$$\begin{aligned} I &= |U_1 + U_2|^2 \\ &= |a\exp[-i\phi] + a\exp\{-i[\phi + \Delta\phi]\}|^2 \\ &= 2a^2\{1 + \cos[\Delta\phi]\} \end{aligned}$$

This then represents the original brightness, crossed by fringes of spacing

$$2\{1 + \cos[\Delta\phi(x, y)]\}$$

That is, any local deformations or distortions will be revealed as local fringes. Holographic interferometry is more suitable for detecting the bulging or swelling of a surface, rather than for surface stretching.

A second technique is time-averaged holographic interferometry, which is usually applied to a vibrating surface. If a hologram is made of the vibrating surface, the reconstructed image will be found to contain a pattern of interference fringes, and by taking holograms at different frequencies, the various modes of vibration can be determined.

Real-time holographic interferometry is similar in principle to the double-exposure technique, except that the object forms one of the two waves—for example, $U_2(x, y)$. The fringe patterns produced follow the motion of the object. It is necessary to expose, process, and replace the holographic plate, and its repositioning must be accurate to within one-quarter of a micrometre. Thermoplastic holographic plates which can be processed in situ are now available. The use of pulsed solid-state lasers, with much higher brightnesses, can obviate the need for the extremely stable mountings needed for continuous lasers, by reducing the photographic exposure-time to a fraction of a second. However, such lasers have a shorter coherence length.

2.4.2 Applications of optical holography

Most of the NDT applications have been in the aerospace field, e.g. for composite panels, honeycomb structures, and bonds and disbonds in adhesively-bonded structures. The specimen is given a slight stress either mechanically or thermally, and non-uniform effects due to defects are shown by fringe anomalies. Holographic NDT is particularly useful on complex shapes where other NDT methods, such as ultrasonic testing, are difficult or time-consuming to apply. Successful applications in the vehicle tyre industry and to printed-circuit-boards have been reported.

2.4.3 Speckle

The properties of coherent radiation may be used directly for non-destructive testing without recording a hologram. If laser light is scattered from an object, the surface appears speckled: that is, it appears to be covered in fine light and dark areas which move as the eye is moved. A qualitative explanation is that each element of speckle represents the smallest area which the eye (or an optical system) can just resolve, and since this area may be quite large and irregular, compared to the wavelength, the light scattered from it will be made up of a number of waves with random phase differences. These waves interfere with one another to produce a resultant intensity which can vary from zero to a maximum value. Statistically, the distribution of the intensities of resolvable areas is random, within these limits, and so each area is likely to have a different brightness to its neighbour, so producing the speckle effect.

The speckle pattern is therefore related to the detailed surface structure (and to the resolving power of the system used to view or record it). Reducing the resolving power increases the apparent size of the speckle.

Speckle can therefore be used to detect movement of a surface and to detect fatigue effects causing surface distortion, by recording the speckle image of a test surface on a photographic plate. After processing, the plate is replaced in exactly the same position and acts as a negative mask, so that correct replacement gives a uniform minimum transmitted field. If the surface now moves, due to the development of fatigue defects or other causes, the matching is no longer perfect, transmission is increased, and a signal is recorded.

2.4.4 Electronic speckle pattern interferometry (ESPI)

Speckle patterns can be used as an inspection technique, without the need for photography, by using a closed-circuit television (CCTV) camera.

The television camera system should preferably be digital output and be equipped with a digital framestore, a choice of filters (bandpass video), and the means for image subtraction. The set-up of the equipment for vibration mode viewing, or surface displacement measurement, is shown in principle in Fig. 2.2. The procedure is to adjust the system aperture and the filter to produce the best speckle uniformity on a stationary object. The object is then vibrated at resonance and the