PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Future of Ultrasonic Examination in Engineering

J. M. Coffey, G. Oates and M. J. Whittle

Phil. Trans. R. Soc. Lond. A 1979 **292**, 285-298
doi: 10.1098/rsta.1979.0062

Phil. Trans. R. Soc. Lond. A. **292**, 285–298 (1979)
Printed in Great Britain

The future of ultrasonic examination in engineering

By J. M. Coffey, G. Oates and M. J. Whittle
Non-Destructive Testing Applications Centre, Central Electricity Generating Board,
North Western Region, Scientific Services Department, Timpson Road,
Manchester M23 9LL, U.K.

Ultrasonic testing is already essential in constructing and operating modern engineering plant, where it is used to detect and measure metallurgical defects which could undermine plant integrity. Safety requirements and the costs of component failure are powerful incentives to apply ultrasonics more widely, and to improve its reliability and efficiency. In particular, ultrasonics is needed to detect planar defects and to measure the defect dimensions which fracture mechanics shows to be structurally significant. The future of ultrasonics will, therefore, be linked closely with the growing use of fracture mechanics to assess defects.

The unacceptable defects in a component must be at least as large as those which ultrasonics can detect and measure. At present, however, the performance of ultrasonics is poorly quantified. Consequently, further research is required into the interpretation of echoes, into the inherent limitations of ultrasonic techniques, and into the consequences of non-ideal testing conditions. Fundamental research will also improve ultrasonics for inspecting Inconel and austenitic steel welds, which present special difficulties.

Improvements in equipment and procedures will extend the scope of both manual and automatic inspections. Automatic tests will increase the reliability and speed of testing, and will operate in hostile environments. In addition, holographic and other signal processing methods will aid defect diagnosis.

1. Introduction

Ultrasonics is only one of several non-destructive techniques which serve in the inspection of engineering plant. The future development of these methods will be in response to the changing demands made upon inspection.

Inspection itself is a very broad subject, concerned with ensuring that the plant is built and run according to its design. In this paper we concentrate upon non-destructive testing and, in particular, its use to detect and measure metallurgical defects in engineering components. There is a need for such testing both during manufacture and throughout the life of the plant. During manufacture the prime objective of non-destructive testing is to ensure that the plant is free of all defects which could cause failure. This can be done directly by searching for structurally significant defects, or indirectly by monitoring the less significant defects which indicate the general quality of a component. Such checks on quality give warning of incorrect fabrication processes or bad workmanship which might well lead to serious flaws. The purpose of non-destructive testing during service is to look for deterioration in the plant so that adequate warning is given of the need to repair. In addition, knowledge of such deterioration may prompt a review of the operating conditions. Indeed, operating conditions inappropriate to the design of plant play a large part in many of those failures which do occur.

Confidence in engineering plant is based largely upon experience of the fabrication processes and of the operating behaviour of similar plant. Nevertheless, every reasonable precaution must be taken to ensure plant integrity. This is especially important nowadays because of the public concern for safety, reflected in the statutory inspection requirements of, for instance, the Factories Acts, the Health and Safety at Work Act and the Nuclear Installations Acts. In addition, there are strong economic incentives to ensure that an installation continues to function; apart from the cost of repairs, the cost of lost production when an unexpected failure lays highly efficient plant idle are usually very high. For example, in the electricity generating industry the differential fuel cost associated with loss of one 210 MW nuclear generating unit is currently estimated at £60000 per day. As plant increases even further in efficiency and capital cost, and as the consequences of failure become even less acceptable, there will be even wider use of existing non-destructive testing methods, with growing pressure to extend their scope and effectiveness.

There are already several techniques, including ultrasonics, which are applicable to surface-breaking defects, and probably most inspection time is occupied with these. Surface defects, however, are usually just ground out, so there is rarely a need to measure their depth accurately. For subsurface defects radiography has been the traditional method and is still used widely, particularly for thin walled components and castings. This technique is particularly well suited to quality control because the defects which denote bad workmanship, such as slag inclusions and porosity in welds and castings, give clear shadows on the radiograph. Moreover, the radiograph itself is a direct, permanent record of the test. On the other hand, radiography, because of its safety hazards, is inconvenient and expensive so ultrasonics has long been an attractive alternative for volumetric inspections. In addition, in recent years the poor sensitivity of radiography to cracks and other planar defects has become appreciated. Considering that fracture mechanics has clearly demonstrated that these defects are the most serious, there is now grave doubt concerning the ability of radiography to prove a component fit for service. Moreover, even if radiography does reveal a crack, only its length parallel to the radiograph can be measured. By contrast, ultrasonics is sensitive to planar defects, and can also give useful estimates of the particular defect dimensions, like extent through the wall thickness, which fracture mechanics has shown to be the most important. This means that ultrasonics is the only generally applicable technique capable of enforcing the type of objective defect acceptance standards, based on fracture mechanics, which is necessary if plant integrity is to be ensured. Ultrasonics also has the advantages of being safe, quick to use, and applicable in hostile environments. Until recently its principal disadvantages compared with radiography have been the lack of a permanent, pictorial record of the inspection, and the subjective way in which the ultrasonic echoes are interpreted in terms of defect size and type. Considering all these points, of all the non-destructive inspection techniques, ultrasonics is the one with greatest potential for development and exploitation.

The aim of this paper is to identify the demands likely to be placed upon ultrasonics and to examine the areas for research and development if the technique is to meet these demands. Most examples in the paper are drawn from C.E.G.B. experience, but they illustrate trends in other high technology industries such as nuclear, aero-space, oil and chemicals. In §2 we consider the specific types of demands which will be made upon ultrasonic inspection in the future. To meet these a greater understanding of the basic physics of the ultrasonic techniques and also improved equipment are needed. Improvements which will result from a deeper understanding are discussed in §3. Specific subsections consider defect detection, defect measurement and the special, extra problems posed by austenitic steel. This discussion is complemented by §4 which deals with improvements in the mechanics of inspection. Finally, in §5 we summarize the main points of the paper and discuss the changing attitudes of engineers towards inspection brought about by the need to ensure plant integrity.

2. FUTURE DEMANDS ON ULTRASONIC INSPECTION

The principal requirement placed upon ultrasonics is to ensure the absence of serious defects and so demonstrate that a component is fit for service. The quality control function of ultrasonics, though important, is necessarily secondary to this.

To decide whether or not a defect is structurally significant clearly requires a reliable means of assessing significance, and this is provided by fracture mechanics. For this reason the link between ultrasonic testing and fracture mechanics has always been close, and the future development of ultrasonics in engineering will accompany the growing use of fracture mechanics. Already fracture mechanics has been used to set standards of defect acceptance for new plant and to assess defects in existing plant which have been revealed by routine inspection. To make full use of this partnership between ultrasonics and fracture mechanics a far clearer understanding of the limitations of ultrasonics in detecting and measuring defects, particularly planar defects, is needed. The effects of defect orientation and shape on the detection and diagnosis of defects is insufficiently understood, and the accuracy of defect size measurement by the traditional ultrasonic procedures has not been generally established. Research in this field is therefore necessary to quantify the performance of ultrasonics. This in turn will indicate the degree of conservatism appropriate to fracture mechanics' assessments of defect significance. It will also show the sizes of defect which it is meaningful to specify in those defect acceptance standards which are to be enforced by ultrasonics.

In recent years considerable use has been made of Inconel and austenitic stainless steel welds and castings, particularly in the chemical industry and in nuclear power plant. Hitherto such components have been regarded as uninspectable by ultrasonics and have merely been radiographed. There is now a need, however, to demonstrate that such welds and castings are free from significant defects, as determined by fracture mechanics. Progress in understanding ultrasonic propagation and defect detection in these materials is discussed in §3*c*. In addition, successful inspection will require that techniques for measuring defects be developed and their accuracy determined.

On account of the lost production time, inspection can prove expensive. Consequently, it is economic to do only the smallest amount of inspection consistent with safety and reliability. This is particularly so when an examination involves either commissioning special test equipment or extensive preparation of the component, say, by stripping paint or by grinding welds. Clearly, to make any quantitative estimate of the efficiency of an inspection, and hence of the sparsest examination which will suffice, it is necessary to have studied the reliability of ultrasonics. The need for similar studies, to demonstrate that ultrasonics can be used confidently with fracture mechanics, has already been mentioned.

Again, to keep outage times short, there is pressure to develop rapid, reliable inspections. In most cases where the component's geometry allows, this will mean the use of automatic equipment for scanning the ultrasonic probes, and for data recording, reduction and display. An example of a simple but effective automatic inspection is the on-line testing of tube or rod during manufacture. By means of ultrasonics, defects can be detected almost as soon as the process goes awry and so high production rates are possible without the risk of miles of scrap. Examples in which more complicated automatic tests are required are the periodic 'in-service' inspections of Light Water Reactor pressure vessels, and of the pipework of the C.E.G.B.'s Dinorwic Pumped Storage Scheme. In these situations automatic equipment is required for speed, and in addition to attain the high accuracy and reproducibility necessary if a comparison of sequential inspection records is to reveal small amounts of defect growth. Holographic methods, though slow at present, are particularly attractive because of their accuracy. Reactor inspection also illustrates the demands for techniques which function in hostile, radioactive environments. High temperature and underwater inspections, particularly at sea, are also challenging problems.

In certain situations a fracture mechanics' assessment of defect growth may indicate that periodic inspection is not sufficient and that continuous surveillance is required. An example of this from C.E.G.B. experience concerns a crack in a turbine casing; this could not be repaired, nor was replacement possible within eighteen months. Because of uncertainties in the stresses and mechanical properties, growth of the crack was monitored directly, while the casing was at 500 °C, for nearly two years. In this case an electrical potential drop technique had to be used since ultrasonic methods were not sufficiently advanced. The demand for such continuous monitoring by ultrasonics will grow as its economic advantages become appreciated. In particular the value of fixed monitoring devices in a commercial fast reactor would be extremely high because of the difficulty of scanning transducers under the liquid sodium coolant.

These, then, are the principal areas in which pressure is being brought to improve the effectiveness and speed of ultrasonic inspection. We look now at the advances which await a better understanding of the physics of inspection and a wider appreciation of ultrasonics by design and construction engineers.

3. Advances arising from improved understanding

As with all techniques, there are constraints on the application of ultrasonics, and limits to its performances. In this section we assess the deficiencies in our current understanding of these matters and indicate the advances which appropriate research will make possible. It is already clear that some constraints and limitations are inherent in the inspection techniques since they stem from the finite resolution of the equipment, from the way elastic waves propagate and from the scattering properties of metallurgical defects. Other limitations arise from non-ideal testing conditions; these, however, are of great practical significance since ideal circumstances are rarely encountered outside the laboratory.

To help the reader appreciate the subsequent discussion, we outline in (*a*) the most common, manual inspection method; (*b*) and (*c*) are concerned with the problems of defect detection and size measurement respectively, though these aspects are influenced largely by the same parameters. It is next appropriate to discuss how a clearer understanding of the limitation of ultrasonics will bring about important changes in the defect acceptance standards used to judge components suitable for use. This, therefore, is the subject of (*d*). Finally, (*e*) considers the additional problems in inspecting and in choosing defect acceptance standards for austenitic welds and cast materials.

(*a*) *A brief description of the basic ultrasonic method*

At present most ultrasonic inspections are carried out by skilled operators using simple, portable equipment. The operator scans a small piezoelectric probe across the surface of the component, using a fluid such as paste or grease to couple the probe acoustically to the metal. In the usual 'pulse–echo' mode the one probe acts alternately as transmitter and receiver. The probe is excited by a voltage spike from the 'flaw detector'. Pulses of sound back-scattered from defects and from geometrical features of the component are detected by the probe and amplified, rectified and smoothed electronically, again by the flaw detector. 'A-scan' display is the most common; in this the amplitude of the echo is displayed as a function of the time of flight on the cathode ray screen of the flaw detector. Usually, to detect defects lying in different orientations, several probes are required, each generating a sound beam at a particular angle to the component's surface. As he scans the probe, the operator interprets simultaneously the changing features on the screen, noting any defects which seem significant. Detailed interpretation involves measuring echo range and the probe's position, but mainly requires considerable skill and experience. Typically, test reports are hand written and show significant defects plotted on a sketched drawing of the component.

(*b*) *Defect detection*

Clearly, the first requirement in defect detection is that the ultrasonic beam pass through the appropriate regions of the component. This means that the ultrasonic operator must have adequate access. It also severely limits the shapes of component which are suitable for ultrasonic examination and this is one reason why radiography is still used widely for castings. Nevertheless, problems can often be circumvented by modest changes in design. More effective inspection, therefore, will result from the growing appreciation by engineers that the constraints upon inspection must be considered during design. A simple example is where pipes with different external diameters must be joined. Welding them together directly will give the weld a sloping surface and there will be discontinuities in the slope at the toes of the weld. These will prevent an ultrasonic probe from scanning over the surface and so it will not be possible to inspect substantial regions of the weld. The problem is overcome by turning down the last few inches of the thicker pipe until its external diameter matches that of the other pipe. The weld can then join the two pipes smoothly.

Provided the beams search the defective region, a defect will be detected when its echo rises sufficiently far above the background noise and above larger interfering echoes. The signal's strength depends on the amount of sound transmitted into the component and, more fundamentally, on the reflecting properties of the defects. The noise and interference usually come from scatter from grain boundaries and non-metallic inclusions within the material, and from reflexion from geometrical features of the probe and of the component under test. Because of this, inspection at high sensitivity is possible only if the material quality is sufficiently good, and if the component's shape is suitable. An example is provided by butt welds in plate and pipe. Slag inclusions left by careless welding can cause a background of small echoes which impair effective inspection for more serious defects. Also for a thorough inspection it is necessary to grind away the irregular weld cap. This prevents unwanted echoes which could mask defect signals, and allows the probe access to all parts of the weld. Furthermore, a poor surface finish on welds or other components will cause loss of acoustic coupling and hence erratic variations in test sensitivity. This again can prevent defects being detected and cause serious problems in interpretation. We see, therefore, that the demands placed on ultrasonics to ensure fitness for purpose have in turn implications for the shape of the component and for the quality of materials and fabrication processes. In particular, the introduction of defect acceptance standards based on fracture mechanics does not sanction a decrease in quality. Rather, high quality is now required not just to promote good workmanship, but because it is actually necessary if ultrasonics is to enforce the fracture mechanics' standards.

It is essential that an inspection detect planar defects. Some guidance concerning their likely orientation has to be given since an inspection which aimed to find any defect, regardless of its orientation, would be prohibitively time-consuming and tedious. Also it would require extensive preparation of the component to give the ultrasonic probes adequate access. In manual inspection, probes are used one at a time in the pulse–echo mode and several beam angles are necessary to increase the probability of detecting the specular reflexion from smooth cracks, or else the weak, diffuse scatter from rough or jagged cracks. Research is therefore required to indicate the smallest number of probes which provides the required level of confidence in the test. Similarly, research will show the relative benefits of pulse–echo testing and of methods which use separate transmitting and receiving probes in tandem. These latter methods are probably the best for detecting vertical cracks in the very thick-section welds being used nowadays in pressure vessels. One constraint on multiple-probe techniques is that a jig is required to hold the probes and this implies an automatic inspection. With all testing methods reliability can be increased by increasing the sensitivity of the equipment, but only to a limit set by interfering echoes. Thereafter, the reliability probably decreases.

At present the problems of quantifying the loss in effectiveness caused by limited sensitivity, restricted beam directions and non-ideal surface finish are only partly solved. There are considerable difficulties in determining the probability of not detecting a notional defect. One direct experimental approach is to organize large-scale examination trials in which many operators assess components which are later examined destructively (Heddon 1976; Jessop *et al.* 1977). Another and complementary approach is to study the variables individually by theory and experiment. A paper recently published (Coffey 1978) contributed to this by using simple models of reflexion from metallurgical defects, such as smooth and rough crack-like reflectors, to estimate the probability of their being detected at various tests sensitivities. This sort of work clearly has application to the 'incredibility of failure' analyses which form part of the safety cases for modern nuclear power plant. It also has implications for the echo amplitude threshold levels set by the A.S.M.E. codes and discussed in (*d*). However, understanding fully the reflecting properties of even elementary obstacles is still a challenging problem in elastic wave diffraction theory. The inverse problem of interpreting echo patterns in any rigorous way is largely uncharted ground. When one considers the irregular form of metallurgical defects and the effects of entrapped corrosion products and applied stress on their ultrasonic reflexion properties, one appreciates the scope for useful research. It is also important to note that many of the difficulties with sensitivity and spurious echoes are equally present in automatic inspections. In particular, the problems set by geometrical form and surface profile affect the performance of new imaging techniques like ultrasonic holography so strongly that practical application of these techniques may remain limited to only the most simply shaped components.

(*c*) *Defect size measurement*

Although ultrasonics has been used for many years to measure defects, it is only comparatively recently that the most common, pulse–echo methods have been regarded from a physicist's point of view and their accuracy questioned in a quantitative way. By contrast, phase-sensitive imaging techniques like ultrasonic holography are much better understood (see §4*b*).

Early attempts to measure defects in pulse–echo tests compared the echo amplitude with that from a calibration reflector, such as a saw cut or flat-bottomed hole. However, echo amplitude depends as much on the shape and orientation of the reflector as upon its size, and growing appreciation of this is causing these naïve methods to fall from favour. In future we expect methods which use only echo amplitude to be restricted to a few special situations in which the defects are small, and have been shown to give good correlation with the calibration reflectors. An example of this is the assessment in large rotor forging for non-metallic inclusions along the bore.

It is now quite widely appreciated that the only generally reliable way of measuring a defect's extent is to locate the opposite edges of the defect and measure the distance between them. In conventional (non-holographic) inspections this involves displacing the probe so that the beam moves from one edge to the other, and noting the change in echo range and probe position. We see, therefore, that defect size measurement is really only possible when the echoes arising from the defect edges are resolved. In holographic methods the resolution is determined by the holographic aperture. For conventional, incoherent inspections the paper by Coffey (1978) relates the limit of resolution to the pulse duration and ultrasonic beam width. Typical values in weld inspection are 2–10 mm. Moreover, this paper argues that, in general, there are random errors inherent in defect size estimation which can not be much less than the limit of resolution. These errors are due jointly to the limited resolution and to the unpredictable nature of metallurgical defects. Further errors come from determining an echo's range, and from variations in acoustic coupling into the component due to an uneven surface profile. In addition there can be significant systematic errors in both conventional and holographic techniques associated with recognizing which features in the echo display correspond to the edges of the defect.

A fully satisfactory answer to these questions in defect measurement will require thorough study of the morphology of metallurgical defects and the diffraction of elastic waves from them. At present, however, it appears that conventional inspections are not able to distinguish the detailed structure of defects sufficiently well that small cracks can be distinguished unequivocally from innocuous defects like pores and slag inclusions. This has important implications for the type of defect acceptance standard which can be enforced by ultrasonics, and we enlarge upon this in the next subsection.

(*d*) *Ultrasonics and defect acceptance standards*

Defect acceptance standards specify the maximum size of defect which a customer will tolerate in a component. In general, whenever defects lie outside the standard, the component must be repaired or replaced. This, however, is expensive. Consequently, the level of defect acceptance has to be very carefully chosen so that a high quality of product does not imply an intolerable rejection rate. Furthermore, since non-destructive testing is needed to enforce the acceptance standard, it is essential that the chosen technique be truly capable of distinguishing the acceptable defects from the unacceptable. It happens that the gradual replacement of radiography by ultrasonics, without an accompanying change in acceptance standards, has led to ultrasonics being expected to enforce standards with which it is incompatible. We will indicate how this situation has come about and show where reforms must be made.

When ultrasonics was first introduced, the standards defining the acceptable defects owed more to the strengths and limitations of radiography – at that time the only available volumetric inspection method – than to any objective assessment of defect significance. Examples of such standards are B.S. 2633 (1973) and B.S. 5500 (1976) which relate to welds in pipework and pressure vessels respectively. Regulations in these standards which limit the aggregate projected area of slag inclusions were clearly written with radiography in mind. Statements that no cracks are acceptable can really be enforced only if the inspection method is sensitive to cracks in the first place, and can also distinguish cracks from the many small and insignificant defects which are inevitable in any component, particularly welds. The insensitivity of radiography to cracks made such standards apparently operable, but concealed an unsatisfactory situation which did not fully come to light until ultrasonics was introduced. With ultrasonics, however, there is a different kind of difficulty; although the technique is sensitive even to small cracks, when the size of a defect, or the spacing of clustered defects, approaches the wavelength of sound, the detailed structure of the reflectors cannot be distinguished. Consequently, ultrasonics cannot identify small cracks unambiguously. This means that the early radiographic standards are incompatible with tests carried out by ultrasonics. Early attempts to enforce such standards to the letter by ultrasonics led to considerable numbers of excavations and repairs for what proved to be no more than insignificant slag inclusions. Furthermore, in certain instances the subsequent repair welds actually contained serious cracks. Despite this, however, engineers are reluctant to relinquish standards which seem to give assurance of freedom from cracks, and so these standards persist. Nevertheless, as the matters discussed above become more widely appreciated, we expect these standards to gradually disappear.

One response to problems due to many extraneous reflectors, whatever their nature, has been to reduce the sensitivity of the ultrasonic inspection. This can be done by imposing 'threshold' levels such that only defects whose echo amplitudes exceed the threshold level are recorded or assessed further. Certain aspects of the American A.S.M.E. codes for the inspection of nuclear reactor pressure vessels specify this procedure. However, the threshold levels, if chosen simply to overcome practical difficulties in the test, may be too high to allow the detection of all unacceptable defects. There is obvious application here for the research into defect detection mentioned in (*b*). In particular, the probability of not detecting cracks at different threshold levels needs much greater study.

More recently the problems with background reflectors have been circumvented by the introduction of fracture mechanics to specify acceptable defect sizes. Usually the acceptable sizes are considerably less than the critical sizes for failure so as to provide a safety factor. There is one constraint on the use of ultrasonics to enforce fracture mechanics' standards, and that is that the tolerable defect sizes be large enough for ultrasonics to measure. This implies that they exceed the limit of resolution for the particular test method proposed (see (*c*)). Unless this is the case, the situation is not much of an improvement on using the old radiographic standards. This has implications for design since it may not be possible to inspect effectively a component in which the critical defect sizes are very small. The penalty for not ensuring an adequate margin between the sizes of unacceptable defects and the sizes which ultrasonics can measure is the continual irritation of unnecessary repairs. Progress will come as design engineers take the crack resistance of a component more into consideration, and also as national and company standards are amended so that defect acceptance criteria become fully compatible with ultrasonic inspection.

(*e*) *Austenitic welds and cast materials*

The discussion so far has assumed that, whatever other problems may arise in mounting an inspection, ultrasonic waves can travel through the material to be tested substantially without hindrance. In certain types of engineering material, however, there are fundamental difficulties simply in propagating the waves. These difficulties arise whenever the grains in the material are not small compared to the wavelength of sound. In this situation high levels of scatter arise at the grain boundaries and can mask signals from even quite large defects. The difficulties are especially present in Inconel and austenitic steels, although ferritic castings sometimes exhibit the same effects because there has been no heat treatment to refine the as-cast structure. There is no practicable grain-refining heat treatment for austenitic materials and the as-cast structure inevitably persists. Forging does modify the structure, but austenitic forgings still often contain large grains which make ultrasonic penetration difficult. For welds the situation is particularly bad because preferential grain alignment along the thermal gradients during welding makes the completed weld elastically anisotropic. When this happens, the ultrasonic beam may be grossly distorted and skewed away from the forward direction. The consequent loss in signal strength makes the detection of small defects improbable. Defect size measurement is very difficult, and special techniques need developing since the usual pulse–echo methods are not applicable.

Until recently there has been no basic appreciation of precisely which aspects of the structure are responsible for the problems. Recent work in the C.E.G.B. (Baikie, Wagg, Whittle & Yapp 1976; Tomlinson, Wagg & Whittle 1978), however, has considerably deepened our understanding and shown that it is possible, by careful attention to the welding process, to control the elastic anisotropy and hence fabricate austenitic welds in a way which permits inspection. A large number of austenitic welds are currently under construction to this prescription at two of the C.E.G.B.'s nuclear power stations. The crucial role played by these particular welds necessitated a volumetric inspection, and this motivated changes in the welding procedure and also a lengthy investigation into the fundamental causes of the inspection difficulties. This illustrates the quite extraordinary steps which the requirement to inspect imposes nowadays.

Other workers have attacked the problem in a different way. Without trying to identify the aspects of the weld structure which are responsible for the very poor signal: noise ratio, they have investigated the benefits of different types of probe (Saglio & Roule 1973) and of signal processing (Ermolov & Pilin 1976; Mech & Michaels 1977). In the latter case the adaptive learning network discussed in §4*b* is showing considerable promise.

At present, therefore, it appears that a combination of control over the metallurgical structure and of signal processing can produce improvements in the inspection of austenitic welds to the point where at least some form of inspection will be possible for most welds. We expect that further research along both avenues will yield yet further benefits so that satisfactory inspection becomes generally possible. It seems unlikely, however, that the low levels of scatter and attenuation found in ferritic materials will ever be attained. This means that sensitivity to defects will be poorer, and so it becomes even more imperative to understand the limitations of the ultrasonic test and to compare these with the requirements imposed by failure calculations.

If there is a statutory requirement to carry out an inspection, and if the significant defects have only a low probability of being detected, there are clear implications for the design of the plant!

4. Developments in inspection equipment

In the previous section we considered the many areas where an improved understanding of ultrasonic techniques will allow these techniques to meet more effectively the demands being placed upon inspection. There must also be parallel developments in the equipment and instrumentation used in testing, and these are discussed in this section. In (*a*) we suggest how manual inspection methods will evolve. The situations in which the limitations of manual testing mean that an automatic inspection must be developed were identified in §2. Specific developments in automatic inspection are discussed in (*b*).

(*a*) *Manual inspections*

Manual inspections are inexpensive and very versatile. They can be applied whenever access to the component is provided and can cope with irregular geometries. They are also the natural choice when only a few components of a type need inspecting since then the development of automatic test equipment would hardly be justified. For these reasons we expect the ultrasonic operator with his flaw detector and his box of probes to remain a familiar figure on engineering sites for many years to come.

To assure the future of manual inspection, good schools are needed to train operators. In addition, certification schemes for operator approval are likely to be proposed for international recognition. In this way a more uniform approach to testing is likely to lead to more consistent inspection results, though there will always be a place for the virtuoso in manual testing. Improvements in reliability can also be expected following the research into echo interpretation mentioned in §3*b* and *c*. In particular this research will give confidence in the test sensitivities used, and should specify the appropriate procedures and equipment for measuring defects. For inspections using A-scan display no fundamental changes in the equipment are expected, though there is an urgent need for specifications to prescribe its minimum performance. An example of such a specification is the one for ultrasonic shear wave probes prepared at the C.E.G.B.'s non-destructive testing Applications Centre and now almost ready for issue (Smallman & Whittle 1978). Specifications can also encourage the appropriate preparation for inspection; the grinding of weld caps to an adequate standard is one example.

The most time-consuming and inaccurate part of A-scan tests is the plotting of the reflectors on a drawing of the component. Recent instrumentation has enabled this to be done automatically while still leaving control of the probe to a skilled operator. An example of this type of semi-automatic inspection is the C.E.G.B.'s B-scan (Harper *et al.* 1978). The probe is attached to a pantograph which transfers the motion of the probe to a series of potentiometers. The output of the potentiometers is related to the position and orientation of the probe and is used to control the position of the recording spot on a storage oscilloscope screen. As the probe is scanned and rotated, the time-base sweep on the oscilloscope screen moves in synchronism. Ultrasonic echoes above a pre-set threshold level are used to brighten the screen. The resulting display is an elevation through the component with the ultrasonic echoes correctly positioned in relation to the component's surface, even when this surface is an arbitrary curve.

The B-scan is proving of great value in interpreting complex echoes. This is because it is usually easier to recognize patterns in the pictorial screen display than in the dynamic behaviour of echoes on the A-scan. In addition, photographs of the B-scan screen provide a permanent record for subsequent interpretation and for comparison with the results of future inspections. For these reasons the benefits of this and other similar instruments are already being realized and their wider use is inevitable. Further improvements will come from increased flexibility in the mechanical and electronic design. The use of focused probes, particularly ones whose focal length is controlled electronically, will enhance the resolution and so give clearer displays. In addition there are several, more speculative areas for development – the use of a quantized grey scale in the display is one.

(*b*) *Automatic inspections*

Despite the versatility and ease of operator-controlled inspections, there are a growing number of circumstances in which a fully automatic inspection is clearly better. The spectrum of problems to which automatic methods apply ranges from the rapid searching of large volumes of metal to the detailed, high-resolution study of individual defects.

Several aspects of automatic inspections will require little specific ultrasonic development since their problems are really ones in mechanical design and control engineering. This is the case with the simplest forms of automatic test which are merely mechanized versions of the manual A-scan. Here the problems peculiar to ultrasonics concern the choices of probe angles and test sensitivity. Guidance in these choices can be expected from the research described in §3. B-scan methods of selecting and displaying the ultrasonic information are also really an extension of the conventional inspection since they still leave considerable interpretation to an experienced operator.

One feature of automatic tests not shared by manual methods is the ability to use several probes in a wide variety of combinations. This gives ample scope for probe development and, in particular, a greater use of large focused probes for higher resolution is expected. Other probe developments will aim to produce devices for monitoring plant continuously at high temperatures or in radioactive regions, the probes being left fixed in place. Here the study of electromagnetic means for generating ultrasound could prove very fruitful.

The other field in which specifically ultrasonic developments will lead to great improvements is that of signal processing and echo interpretation. The aim is to overcome a major disadvantage of manual, and indeed of all, conventional test methods, namely the lack of assurance that the appropriate information has been gathered and that the interpretation is correct. Several automatic data processing techniques are currently being assessed, but two in particular are showing exceptional promise. If this is fulfilled, we anticipate their adoption in a wide range of problems.

The first technique is acoustical holography (see, for example, Coffey & Whittle 1976). Here, by contrast with conventional methods, the amplitude and also the phase of the ultrasonic echoes are exploited. Both 'real-time' and 'off-line' holographic methods have been developed, but the most useful for engineering use will be the 'scanned aperture' one. In this the probe is scanned automatically over the component and signals from internal reflectors are interfered with an electronic reference wave and so used to construct a hologram. This can be transferred to photographic film and reconstructed optically in the familiar way. The holograms can hold information concerning defects over the full depth of the component and this can be recovered as images of the defects by focusing at the different depths. An outstanding feature of the reconstructed images is that a lateral resolution comparable to the wavelength of sound can be attained at all depths (though the depth resolution is not nearly so good). This contrasts with conventional inspections in which the laterial resolution degenerates progressively with range as diffraction spreads the ultrasonic beam. The reconstructed images can also be photographed for permanent record. The increasing demands being placed on the inspection of Light Water Reactor pressure vessels are typical of the stimuli for wider application of holography (Collins 1975; Holt 1976).

The other outstanding signal processing technique is the adaptive learning network (Rose, Niklas & Mast 1976.) This is receiving widespread attention in the U.S.A. In this method it is conjectured that the important information required of a test, such as defect presence, defect type and size, can be related in a purely phenomenological way to a number of experimental parameters. Examples of these are amplitude of signal, peak of frequency spectrum, cross correlation between the signals received by the probe at different positions and so on. The ultrasonic information is digitized and a network is formed whose output depends on combinations of the input parameters in linear, quadratic and cross-product form. The coefficients relating the output to these different combinations are calculated from information derived using known reflectors in test samples. Using these coefficients, the network is then able to analyse the signals from other samples and the coefficients are adjusted in an iterative manner. Preliminary results show that the output contains the required information regarding the defects in the component.

The scope and performance of the method has yet to be fully established but at the time of writing (January 1978), early results are sufficiently good to hold out considerable promise for defect recognition in both ferritic and austenitic materials.

5. Summary and discussion

In this paper we have stressed the growing need to guarantee the safety and reliability of engineering plant. One cause of failures is metallurgical defects and here fracture mechanics, aided by stress analysis and materials testing, allows an objective assessment of a component's integrity. Consequently, fracture mechanics is being used much more widely. We have also argued that ultrasonics is the only satisfactory non-destructive technique for detecting subsurface cracks and other planar defects, and for measuring their particular dimensions required by fracture mechanics. Because of this, the future of ultrasonic testing will be linked very closely with that of fracture mechanics.

Many instances could already be cited where together fracture mechanics and ultrasonics have enabled modern plant to be commissioned and to run. So far, however, these have mainly been situations where, with the plant already designed and built, doubts have been expressed about certain components and so these techniques have been called upon to demonstrate suitability for service. Another common situation has been where routine in-service inspection has detected a growing crack, and this is in a component which it would be most inconvenient to repair straight away. Such *ad hoc* applications of fracture mechanics and ultrasonic inspection will always be necessary since unforeseen problems are bound to arise.

Nevertheless, in high technology industries a more systematic approach to inspection and quality assurance is evolving. This is due to a growing appreciation by engineers of the economic penalties of delaying consideration of inspection till plant construction is far advanced. The American A.S.M.E. pressure vessel codes provide a good example of how inspection is becoming regarded as having a proper place in the plant programme. Here, the requirement to carry out in-service inspection has meant that the whole pressure vessel is appropriately designed, and in particular that the reactor internals can be removed. The motivations for this change in the status of inspection are reliability and cost. Thus, as engineering projects embrace more adventurous designs, newer materials and more demanding operating régimes, engineering judgement can no longer be accepted as sufficient justification for confidence in the installation. Instead it becomes necessary to supplement experience with more specific and objective assessments using fracture mechanics and non-destructive testing. However, such analyses can themselves be very costly and can create unacceptable delays in the construction programme. Consequently, a compromise must be effected and this can only be reached by judging the relative merits of alternative fabrication routes and the precise role of inspection in each route. This also affords the opportunity to ponder the uncertainties in plant design, construction and operation, and also the consequences of a failure. In this way the need for regular in-service inspection may become apparent. Such inspection would almost certainly have implications for the design and fabrication of components which it would, in the long term, prove costly to ignore.

It seems likely, therefore, that we will see wider use of codes of practice, perhaps evolving from the A.S.M.E. codes, which give instruction in determining the required level of inspection. Careful guidance is particularly needed in deciding whether in-service inspection is really necessary since the development and outage costs of such examinations can be very large. Unless the probabilities of failure are carefully weighed against the consequences of failure, considerable expense and effort could be spent in conducting extensive inspections which serve no useful purpose. Codes of practice will also give guidance in the design and conduct of the inspections themselves. Here the improved understanding described in §3 and the more advanced equipment described in §4 should make possible effective, efficient inspections whose level of success is quantified.

The authors are most grateful to the Director General, C.E.G.B. North Western Region, for permission to publish this article.

REFERENCES (Coffey *et al.*)

Baikie, B. L., Wagg, A. R., Whittle, M. J. & Yapp, D. 1976 *J. Br. nucl. Energy Soc.* **15**, 257–261.

B.S. 2633 1973 *Class 1 arc welding of ferritic steel pipework*, clause 8.2. London: British Standards Instn.

B.S. 5500 1976 *Unfired fusion welded pressure vessels*, clause 5.7. London: British Standards Instn.

Collins, H. D. 1975 In *Proc. 9th. Symp. on NDE*, San Antonio, 25–27 April, pp. 313–330.

Coffey, J. M. & Whittle, M. J. 1976 *Phys. Technol.* **7**, 146–153.

Coffey, J. M. 1978 In *Proc. Conf. on Tolerance of Flaws in Pressurised Components*, paper C103/78. Instn Mech. Engng, London, 16–18 May. Bury St. Edmunds: Mechanical Engineering Publications. (In the press.)

Ermolov, I. N. & Pilin, B. P. 1976 *NDT International* December, 275–280.

Harper, H., Jones, H. M., Slinn, J. P. & Spinks, A. H. 1978 *CEGB Report* no. NW/SSD/RR/8/78.

Heddon, O. F. 1976 In *Proc. Third Conf. on Periodic Inspection of Pressurized Components*, paper C205/76. Instn Mech. Engng, London, 20–22 Sept., p. 85.

Holt, A. E. 1976 In *Proc. Third Conf. on Periodic Inspection of Pressurized Components*, paper C234/76. Instn Mech. Engng, London, 20–22 Sept., p. 165.

Jessop, T. J. *et al.* 1977 *Welding Inst. Report 3527/4/77*. Cambridge: The Welding Institute.

Mech, S. J. & Michaels, T. E. 1977 *Mater. Eval.* **35**(7), 81–86.

Rose, J., Niklas, L. & Mast, P. 1976 In *Proc. 8th World Conf. on NTD*, paper 3H-1. Cannes, France, 6–11 Sept.

Saglio, R. & Roule, M. 1973 In *Proc. 7th Int. Conf. on NTD*, paper F-05. Warsaw, 4–8 June.

Smallman, H. & Whittle, M. J. 1978 *Br. J. non-destr. Test.* **20**, 296–302.

Tomlinson, J. R., Wagg, A. R. & Whittle, M. J. 1978 *Proc. 2nd Int. Conf. on NDE in Nuclear Industry*. Salt Lake City, Utah, 13–15 Feb. Also *CEGB Report* no. NW/SSD/RR/25/78.