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

Current Limitations of Non-Destructive Testing in Engineering [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1979 **292**, 163-174
doi: 10.1098/rsta.1979.0050

Phil. Trans. R. Soc. Lond. A. **292**, 163–174 (1979)
Printed in Great Britain

Current limitations of non-destructive testing in engineering

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The paper gives an introductory review of the current status of non-destructive testing techniques as used in engineering practice, and the various ways in which they are employed to improve quality and reliability.

All structural materials are inherently 'defective' if one inspects at sufficient sensitivity and many of the limitations of present-day testing techniques centre around the difficulty of characterizing defects in a sufficiently quantitative way so that thresholds can be realistically set.

Many techniques rely on interrogation with a sensing probe and as a consequence of this approach there are many limitations associated with ambiguity in interpretation. Improved means of signal processing and data presentation are being evaluated to minimize this ambiguity although it must be realized that the conditions under which engineering inspection has to be carried out in practice often preclude the use of optimum solutions. The paper identifies areas where scientific attention might be directed so that the techniques are more acceptable to present requirements.

Introduction

This meeting is a landmark in efforts over many years to encourage scientific involvement in a subject whose progress of development has hardly done justice to the potentially important role that non-destructive testing plays in support of engineering practice. It is also a landmark in bringing together the medical health diagnostician and his counterpart in industry who is now, by analogy, becoming known in some quarters as the mechanical health diagnostician.

Although the problems and technical challenges are somewhat similar in the two fields and many of the diagnostic techniques have independently developed along parallel lines, there are two very important differences which have undoubtedly affected the rate and direction of progress in the two fields. In the medical case, it might be said that there are only two basic products to be inspected, male and female, differing only slightly in constructional detail and surface profile, and with an extremely long evolutionary time-scale! In the engineering case there is an infinity of different products with designs changing in many cases quite dramatically and on an extremely short time-scale compared with reasonable non-destructive testing development times; this considerably complicates the requirement and provides a serious limitation to technique standardization. Secondly, in the medical case changes in product design and modification in the manufacturing process are largely outside the terms of reference, or indeed the capability, of the profession; primary research effort can therefore be directed to the diagnosis and cure of defects. In the case of industrial products, design and production have always been considered the pre-eminent engineering challenges, with inspection, testing and defect diagnosis relegated to very subsidiary roles.

By the usually accepted definition, non-destructive testing relates to 'those techniques that check compliance of materials quality, or structural integrity, to agreed specifications without in any way affecting the serviceability of the objects so tested'.

In highlighting limitations where further scientific stimulus and support could be provided in the two specific non-destructive testing subjects chosen for discussion (i.e. radiography and ultrasonics) one needs to take cognisance of the fact that, despite limitations, there has been praiseworthy progress and achievement in application over the years to meet specific demand. This has been brought about by an increasing band, largely of dedicated technicians, working against the odds not only of design change and design multiplicity, but of nature, the elements, unsympathetic managements, inadequate budgets, unrealistic specifications, and often with non-optimized techniques and instrumentation. It is indeed very encouraging that the Royal Society has recognized the need for this particular discussion meeting which, if it achieves nothing else, should serve to set a 'seal of respectability' on a subject that, one suspects, is felt by the academic world to be altogether too technologically and commercially orientated for recognition as a suitable scientific challenge. This problem is not peculiar to non-destructive testing but is generic to areas of specialist technical application which bridge a variety of disciplines and interests and so form a 'grey area' as regards both industrial and academic responsibility.

Non-destructive testing application in engineering

In manufacturing industries, non-destructive testing has developed primarily as the 'crack detection' function of inspection and so, with chemical analysis, metrology and mechanical testing, shares the role of maintaining product quality to acceptable standards. Another more positive role for non-destructive testing in manufacturing industry is the improvement of quality by improved design or process control from the non-destructive testing 'feed-back'. These are undoubtedly important areas for further development and application.

In the fabrication industry non-destructive testing has also developed as a means of monitoring quality; it often serves as much to raise standards of workmanship, and hence maintain quality levels, as to detect and remove defective products.

Another role for non-destructive testing, which has assumed much greater importance, is as a means of monitoring plant and structures during service and throughout the operational lifetime of a product. It is in this role that judgement and decision can be vital in terms of life and property. Since design for subsequent inspection is a requirement that is still rarely considered seriously, and since in-service inspection is often a field operation tightly linked to the economics and pressures of maintenance schedules, it is in this area where many of the limitations of present-day non-destructive testing techniques have been particularly highlighted. High temperature and the presence of lagging in process plant, radiation and contamination in nuclear reactor installations, accessibility problems in fabricated structures and underground pipelines, and the all-important consideration of sheer survival when underwater structures are inspected all serve to make the 'sharp end' of non-destructive testing populated by dedicated technician conscripts rather than by volunteer scientists! Owing to the problems and hazards associated with in-service inspection this is also the area where more research is urgently needed to develop automatic continuous surveillance techniques not only for temperature, pressure and stress but also for crack initiation and the degradation of materials as well as into methods of analysing all of these variables unambiguously in terms of life expectancy.

It will perhaps be apparent already from what I have said that limitations to progress and achievement in engineering non-destructive testing are by no means entirely of scientific origin.

Indeed in this subject it is of no great help or relevance in the short term to produce theoretical solutions to abstract problems unrelated to practice. Equally, of course, one must stress that it is dangerous to develop and introduce empirical techniques without proper scientific understanding or without rigorous evaluation of the practical variables, as has been the case so often in the past. The balance is a fine one; erring too much in either direction can easily lead to misunderstanding and disillusionment. While I realize that this meeting has been designed to emphasize scientific limitations and means of alleviation, it is certainly neither appropriate nor sensible to try to separate science from reality in this very practical subject.

DEFECT SIGNIFICANCE

In designing non-destructive testing techniques one can conveniently divide defects into two basic categories: those where there is an involvement with a surface and those which are entirely confined to the interior of the material. The defects themselves can stem from 'original sin' in the material carried over from the primary manufacturing stages; they can be introduced as a result of a fabrication process (e.g. welding, casting or bonding); or they can be generated as a result of service (e.g. fatigue and creep damage, corrosion or microstructural degradation). Ultrasonics and radiography are primarily needed for locating defects which are entirely within the interior, or on the far surface of a component to which access is restricted. For defects on an accessible surface other methods of location by visual inspection, magnetic flux leakage or the disturbance of eddy currents are usually easier and more effective.

In developing non-destructive testing techniques it is necessary to realize that all materials are inherently defective; indeed the achievement of many mechanical and physical properties depends on a controlled distribution of defects on a microscopic scale (such as dislocation networks, vacancy populations and grain structure). In other cases, small defects can be present which are in no way detrimental to performance. One of the big limitations with present non-destructive testing techniques relates to the difficulty in setting realistic thresholds to separate defects that are potentially harmful *under given operating conditions* from those which are harmless and where rejection is unnecessary and costly and where subsequent repair could itself be a greater hazard to component integrity.

Through lack of positive guidance, too often in the past levels of rejection have tended to be set by the resolution limit of the testing procedure, or in the case of surface defects by the limit of detectability with the unaided eye; such arbitrary criteria naturally have no particular relevance in terms of operational performance.

Defect significance depends on a number of quantifiable factors, such as stress distribution, defect characteristics, environment and materials properties. A deeper scientific understanding of the relations between these and failure mechanisms, crack initiation and crack propagation in engineering materials is certainly required. However, it must be realized, that in a given situation defect significance also depends on subjective judgements related to a considered analysis of the consequences of failure and the strong forces of commercial competitiveness. One of the limitations to scientific progress in non-destructive testing in the past has undoubtedly been the isolation of non-destructive testing development from materials research and from back-up destructive testing and failures analysis, with a consequent lack of communication on technique requirements, realistic specifications and performance criteria. It is as though one could expect medical diagnostic techniques to be properly developed without a clinical knowledge of anatomy or without an understanding of the factors that cause disease and geriatric deterioration.

However, even if defect significance could be scientifically quantified a basic problem remains. With both ultrasonics and radiography a decision to reject has to be based not on a knowledge of the defect size itself exceeding a specified value but on the defect response to a particular interrogating agent exceeding a specified threshold. Without doubt this represents a very serious limitation since numbers, analogue signals or image contrast arising from a test can easily be misjudged or misinterpreted. In addition, comparison responses are obtained with calibrating devices that often bear little relation to the behaviour and characteristics of the defects in question.

Perhaps the biggest scientific contribution required at the present time is a quantitative study of the various factors that have a significant influence on the interaction between defect and interrogating medium and, coupled with this, more work on response signal analysis to ensure that the variable being monitored has a uniquely varying relation with the characteristic of the defect that is of primary concern.

Limitations in ultrasonics testing

Where ultrasonic inspection is used in the pulse–echo mode, there are many features of a defect that can have a significant influence on the interrogation response and there are also many features of the material itself that influence the propagation of the ultrasound into and out of the sample. Theoretical modelling has so far tended to concentrate on an understanding of wave interaction with simple shapes in a uniform isotropic medium and this, of course, can be at the best only a first approximation to the real situation. Work at Harwell and elsewhere is concerned with the effects of defect orientation, defect roughness and liquid filling of cracks, which are all important variables that need to be considered in the practical case.

In engineering practice today, fracture mechanics analysis is being more widely adopted. This recognizes the fact that defects are inevitably present in any structure but that these will be benign and not lead to sudden failure unless or until they grow to a certain critical size determined by the fracture toughness of the material and by the level of the local stresses in the neighbourhood of the crack during its service life. As a result of adopting this design principle, the manufacturer and operator have a responsibility to demonstrate that flaws in *all* of the regions of concern can be *reliably* detected and then their size determined *unambiguously* with respect to the dimension of main concern in the fracture mechanics calculations; that is, the depth in relation to the section thickness. This raises a number of important non-destructive testing requirements which are by no means satisfactorily fulfilled at present.

The first requirement relates to the reliability of defect detection. As much of this inspection is, of necessity, carried out on large structures of complex geometry, and under difficult conditions, manual ultrasonic scanning is usually necessary and the reliability of detecting defects with a variety of possible orientations is often not as high as plant integrity demands.

Statistics on the reliability of defect detection are currently being obtained from a series of controlled tests in which thick-section weld samples are being circulated to non-destructive testing departments in different organizations. In one such test where the weld has been subsequently sectioned, it has been established that only between 50 and 90 % of the total defects found to be present were recorded by the five ultrasonic testing teams involved. It is also of interest to note that a significant factor influencing these results was operator error in recognition and reporting (Anon. 1971).

This illustrates well the point that the capability of current inspection procedures is far too dependent on the skill, experience, judgement and integrity of individual operators and the constraints under which they have to perform their tests and interpret their results. There is a great need for more automatic inspection. Most present non-destructive test methods require a subjective assessment of quality from an image, either a film in radiography or a screen in ultrasonics, and the level of inspection cannot be consistent. Automatic techniques remove any ambiguity once levels have been set. Automatic systems are also more rapid than manual one although they tend to lack versatility and each unit has to be tailored to a particular inspection problem.

Another factor of concern is that, owing to the occurrence of acoustic mismatch at structural features such as grain boundaries in some materials (e.g. austenitic stainless steel) spurious reflexions can lead to ambiguity. The characteristics of wave propagation in anisotropic structures can also lead to erroneous interpretation of defect positions. These effects can be pronounced because the wavelengths of the ultrasound used (0.5–5 mm) are the same order of magnitude as many of the structural features, so that diffraction and interference effects are exaggerated.

The second requirement is the need to determine the size of defects with sufficient accuracy. Most ultrasonic techniques rely on amplitude measurement to gauge the size of the reflecting discontinuity or map out its extremities. In some situations this has proved an unreliable method of accurately defining the critical through-thickness dimension of a defect; this is a limitation when it comes to matching ultrasonic test data to fracture mechanics predictions. As an alternative approach, current work at Harwell by Silk (1977) is moving away from amplitude measurement entirely and focusing attention on techniques based on measuring the time it takes for a sound pulse to reach the defect and for the ultrasound diffracted from the extremities of the defect to reach a second transducer. Knowing these transit times, the through-thickness dimension (or depth) of a defect can be computed and, if required, the profile of the defect displayed as a two-dimensional record.

This and similar developments are demonstrating the need to consider non-destructive tests as an integrated assembly of interdependent factors all of which need to be properly specified and controlled. Thus in the defect-sizing studies, ultrasonic pulse length and beam spread characteristics, material and defect properties, signal:noise enhancement and recorder characteristics all need to be considered together in order to achieve optimum test performance. Non-destructive testing development has suffered in the past because the route to optimization has often been sought by sequential study of the parts of the system.

The third requirement is the ability to monitor growth of cracks during service in order to have advance warning when a crack is approaching critical size. This form of in-service surveillance has perhaps reached its peak of sophistication with reactor pressure vessels in nuclear power stations. Working to code requirements has particularly highlighed present weaknesses in defect sizing, the problems of structural variability in weld metal and the very considerable, and perhaps overriding, limitations introduced by the engineering problems caused by restricted accessibility and by the associated radiation hazard. Because of these limitations attention has recently been focused on the phenomenon of acoustic emission as a basis for a possible alternative surveillance technique and for positively differentiating 'active' cracks from benign cracks, by detecting the stress wave pulses emitted as crack extension occurs under the influence of applied stress. This is a technique, complementary to the more passive methods of ultrasonic flaw detection, where a considerable amount of empirical evaluation has identified both its considerable potential and also its many limitations, and demonstrated the need for a parallel scientific study of emission processes in relation to the materials failure modes with which they are associated.

Work by Scruby *et al.* (1978) at Harwell is attempting to devise a system that allows acoustic emission signals to be detected with minimum distortion and this is already demonstrating the possibility of using the technique as a laboratory diagnostic tool to provide 'signatures' that can be related to different fracturing mechanisms. When these and associated studies are complete there should be more confidence than at present in translating the technique into practical applications. A similar approach if applied to ultrasonics, even at this late stage in its evolution, aimed at developing carefully controlled laboratory studies of beam/defect interaction, might serve to generate fresh confidence in understanding the capabilities and limitations of this technique too.

The introduction of the phase of an ultrasonic signal as another variable in ultrasonic tests has led to the successful development of ultrasonic holography as a means of deriving more spatial information about defect structures within a metal by wavefront reconstruction. The hologram contains the integrated information from the returning ultrasonic signals, related to the phase of an impressed reference signal. At present the hologram information can be converted to a transparency and then three-dimensional information extracted with a reference laser beam. Recording phase and amplitude information as a hard-copy display and then reconstructing optically is a slow and rather limited method of data processing. Systems are being developed for nuclear pressure vessel surveillance, where all of the information from linear (Kutzner & Wustenberg 1977) or raster (Anon. 1977*a*) scans is recorded digitally and then processed to provide whichever presentation is best suited to the particular inspection requirement. Although sophistication in data processing can help to automate ultrasonic inspection and provide impressive displays (e.g. B-scan, C-scan, P-scan and isometric scans) one needs to look very closely at the source of raw data, since sophistication linked to inadequate or suspect data can be extremely misleading and potentially very dangerous. This again points to the necessity of properly characterizing all components of the *whole* test rather than tackling the problem piecemeal.

It is of particular interest in the context of this meeting that the development at Harwell towards an engineering requirement for ultrasonic holography has directly led to the development of an improved real-time scan system, now in clinical use at Moorfields Eye Hospital, in which a rapid mechanical scan of the eye orbit is linked to a variety of data presentational modes, depending on the particular clinical information required (Restori *et al.* 1978). This is a particularly successful example of how cross-fertilization of ideas can occur between the medical and engineering fields. Ultrasonic techniques in both fields have a common requirement for developing a better understanding of transducer performance and there is scope for a scientific study of transducers so that the various parameters affecting performance can be properly characterized for any particular application. Power output levels and beam shapes are of interest in both medical and engineering fields and methods of measuring and monitoring these are being studied. For example, Speake *et al.* (1978) have developed a sensitive laser interferometer which is currently being used to obtain absolute power profiles and this should be of value in assisting further research into this important subject. Transducer arrays with multiplexed excitation for beam angling, dynamic focusing or beam steering are well established for medical ultrasonic scanners where patients can be brought to a central diagnostic installation. However, they have not yet been firmly established in engineering non-destructive testing practice. This is partly because of the great variation in design and geometry of components requiring test and partly because of the greater difficulty associated with operating such devices as part of custom-built systems for in-service surveillance. In the engineering field more interest has centred on non-contact transducers for injecting ultrasound into structures either with electromagnetic acoustic transducers (where alternating forces are generated in the surface of an electrical conductor by an interaction between induced eddy currents and a steady magnetic field) (Anon. 1977 *b*) or more recently by laser pulse impingement (Mallozzi *et al.* 1977).

LIMITATIONS IN RADIOGRAPHIC TESTING

Turning to radiography, the major limitation here is undoubtedly the inherent insensitivity to planar defects and the consequent disproportionate prominence shown by volumetric defects, which generally have less influence on structural integrity. There seems to be no obvious way of overcoming this shortcoming since it is a limitation that reflects the physical nature of X-ray attenuation. However, xeroradiography and various forms of image processing can provide some increase in visual contrast at local density steps and produce some enhancement of features that otherwise might not be easily discernible.

Definition of fine detail has always been a limitation in radiography because of image unsharpness associated with the finite dimensions of the X-ray source. Microradiography is a technique that has shown the capability of revealing structural variability well below that detectable in radiographs viewed in the normal way with the unaided eye. High-magnification images can be achieved either by photographic enlargement of radiographs on extremely fine grained photographic emulsion (contact microradiography) or by using finer focus X-ray sources and producing enlarged primary radiographs (projection microradiography or high definition radiography). Equipment based on developments in X-ray tube construction by Ely (1972) is now available in which the electron beam is focused to a 10–20 μm diameter spot on the anode, from which the X-rays radiate. This has been shown to be particularly effective in inspecting turbine blades for areas of microporosity.

The uprating of operating conditions in modern gas-turbine aero engines has necessitated a considerable reduction in the level of defects which can be tolerated in the turbine blades. These blades are produced by the 'lost wax' casting process which can create micro-pores (0.01–0.03 mm) in the material and these micro-pores are no longer acceptable to any great extent. Up to 1974, a destructive sampling technique was used to monitor the levels of micro-porosity being produced and batches of blades were rejected or accepted on the metallographic evidence determined from sample blade sections. This was a tedious process and used only a small and possibly unrepresentative sample of the total batch.

With conventional X-radiography, micro-pores can easily be confused with the pattern produced by the material structure. However, by using high-definition radiography a satisfactory technique has been developed with a magnification of × 12. With the addition of a fast detector system with a combination of fluorescent screens and film, a radiograph could be produced with an exposure time of only 2 min. This system is now in use at Rolls-Royce Aero Division and has enabled the company to detect and control micro-porosity in turbine blades for several engines (Parish & Cason 1977).

This specialized X-ray equipment has also been shown to be capable of characterizing the extent of bonding of integrated circuit chips and of monitoring micro-welds and this could well lead to more widespread application of the technique (Parish 1976).

This is another example where there is a possible direct carry-over of experience into the medical field. In collaboration with Harwell, C. Buckland-Wright at Guy's Hospital is carrying out radiographic comparisons using a conventional clinical X-ray unit and the Harwell high-definition radiographic unit. Although the work so far has been limited to post-mortem specimens he has shown that, with the micro-focal unit (*a*) the higher magnification image makes it easier to observe structural detail, (*b*) the higher resolution allows finer structural detail to be recorded and measured, and (*c*) the reduction in intensity of the scatter reaching the film gives greater image contrast.

Movement blur is of concern when radiography is extended to observe changes in internal configuration in moving machinery. This is becoming of importance in mechanical health-monitoring procedures where non-destructive testing is being used directly to channel performance information back for design analysis. There is considerable interest in the potential improvement of phosphors to give higher speed and better image resolution. Also, if better radiographic sensitivity can be achieved as a video presentation, sample configuration with respect to the X-ray beam could more readily be optimized for detecting planar defects; much of the interpretation might then be done objectively by image processing techniques. Only in very special situations, such as perhaps alignment and distortion in multi-element nuclear fuel assemblies, is computer assisted X-ray tomography technology likely to find a use in engineering non-destructive testing.

A limitation of radiography arises from the contrast achievable by the differences in attenuation of the sample constituents and there is only limited flexibility by changes in voltage or utilization of absorption edges. However, engineering radiographic inspection has been usefully extended by the judicious use of complementary radiation sources. Neutron radiography is particularly effective in examining samples or rig components that are highly radioactive as a result of nuclear-reactor irradiation. Such samples have too high an inherent irradiation to be radiographed in the normal way but can be inspected with ease by neutron radiography using a transfer technique. Residual core material in turbine blades and oil distribution in machinery are examples that can be revealed with neutron radiography, whereas the image contrast with X-radiography is normally inadequate. Proton radiography also has specialized applications although, at present, as with neutron radiography, adequate results can often only be achieved by bringing the sample to a suitable high-intensity source, be it a high-voltage accelerator in the case of protons or a reactor in the case of neutrons.

Structural variability

Another limitation in the development of engineering non-destructive testing techniques has been that undue attention has been paid to structural discontinuities (such as cracks, laminations and porosity) and as a consequence there has been too little emphasis placed on the need to control and monitor microstructural variability. The 'defects' that one needs to control in engineering non-destructive testing are not restricted to discontinuities in the generally accepted sense. They may be variations in structure, giving bulk or local variations in physical properties or strength, or more insidious variability such as the level and distribution of internal stress, variations in bond strength or the variability of interfacial strength in composite structures. The challenges in this area are twofold: first, understanding the significance of microstructural variability and microstructural degradation on performance and integrity of a component so that levels and tolerances can be scientifically based; secondly, identifying and characterizing physical properties that can be linked monotonically to the structural variation of interest, and then developing suitable testing procedures based on them. The lack of understanding of the significance of inferential methods of measuring properties, including the statistical nature of the correlation between the two parameters, is one which results in a severe limitation to the increased use of non-destructive testing in this area. The lack of understanding of these methods often results in operators using a fixed method when there are several variables affecting the measurement. The results therefore become unreliable and the method, which is intrinsically sound, acquires a reputation for unreliability.

This is a wide-open field for scientific study, and one where ultrasonics and X-rays are but two of many monitoring agents that might be used. Changes in ultrasonic velocity and attenuation and in resonant frequency have already been studied in relation to grain size distribution, 'quality' of castings, surface and internal stress levels, fracture toughness and heat-treatment variations in metals, porosity and aggregate distributions in concretes and fibre loading in composites.

In the radiation field, low-angle neutron scatter is being evaluated to monitor inclusion concentration in complex alloys and positron annihilation is being used by Coleman & Hughes (1977) at Harwell to detect the onset of fatigue damage and hopefully predict residual fatigue life by observing the early stages of structural disturbance, before cracking is initiated.

Property monitoring in general is a particularly fertile field for collaborative research between the physicist and the materials scientist.

CONCLUSIONS

The paper has directed attention to some of the limitations of non-destructive testing which might be resolved by more scientific study. However, one must not forget that there are other equally serious limitations to the successful introduction of non-destructive testing to be overcome based on design complexity, accessibility, management attitudes and commercial considerations. Also, in putting greater scientific emphasis into the development of the techniques one needs to recognize that, as a means of manufacturing control, non-destructive testing as an inspection procedure should properly be seen as an obsolescent activity. In this area its primary function should be aimed towards providing better design, better manufacturing processes and longer operational life and it is to these ends that the long-term objectives should always be directed. In-service inspection, condition monitoring of plant and integrity surveillance are clearly areas of expansion in non-destructive testing where further scientific stimulus could be very beneficial.

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Discussion

A. F. Brown (*Physics Department, The City University, St John Street, London EC1V 4PB, U.K.*). I agree with nearly everything that Mr Sharpe has said, but wish to take issue with him on one point. First, however, I welcome his comments on the lack of interest shown by the academic community in non-destructive testing. A recent survey, which he edited, in *Physics Bulletin* (January 1977) showed that in only two British Universities were the Physics departments concerned with the subject. In Engineering departments the situation was not much better. This affects us in two ways. First, of course, the fundamental research in non-destructive testing which Mr Sharpe called for is not being done. This may help to explain a fact which, I suspect, from the evidence of the programme, will emerge from this conference: this is that sophisticated equipment will be almost the sole property of the medicals. Secondly, non-destructive testing is being taught inadequately, if at all, to students of technological subjects. The result of this must be that Mr Sharpe's aim of designing ease of testing into the plant or aircraft will be postponed for yet another generation.

However, searching for something to disagree with him on, I would like to query his advocacy of ultrasonic holography, at least in the form he described. Holography was originally conceived as a method of recovering phase information; Gabor first thought of it as a method of getting over the limitations of electron lenses but it found its applications with electromagnetic radiation. However, applying the Gabor method to acoustic waves throws away the three advantages which they have over electromagnetic waves. First, with acoustic waves one can generate short pulses, of the order of one wavelength long at the centre frequency. Secondly, since sound travels much more slowly than light, one can time these pulses over the short distances involved in non-destructive testing or in medicine; alternatively, individual echoes can readily be gated out electronically. Finally, one can measure phase; there is no need for a reference beam. Since time-gating is easy, information at differing depths can be obtained by a series of C-scans which may offer advantages other than ease since monochromatic holography has poor depth resolution. I appreciate that very thick metal specimens can be examined holographically but the alternative method of phased arrays of transducers is of more general and easier application. The same is true when biological specimens have to be examined at various depths.

I have suggested a few unsophisticated ways in which ultrasound can be made to do all that holography can. More sophisticated techniques can be devised (and have in fact already been, in connection with seismic pulse testing) with the use of computer processing of time, amplitude and phase information.

P. J. Emerson (*B.C.I.R.A., Alvechurch, Birmingham B*48 7*QB, U.K.*). I was pleased to see that Mr Sharpe included assessment of 'quality' as well as checks on structural integrity in his definitions of the scope of non-destructive testing. In the ironfounding industry, checking the 'quality' of iron castings is an essential feature of the manufacturing process and using ultrasonic velocity measurements for checking the metallurgical structure of high-duty irons is an established technique which would find wider application if robust equipment were available at an economically justifiable price. Similar tests can be used on concrete constructions and, theoretically, are applicable to many two-phase structures.

The use of ultrasonic techniques for measuring 'quality' has not been greatly explored or exploited. Velocity, and frequency dependent ultrasonic attenuation and scattering, are parameters that give valuable information on the structure of materials and are worth further investigation in both engineering and medical applications. A full understanding of the relations, and the provision of robust instrumentation, will reduce the current important limitations in measuring the 'quality' of structures and allow these to be judged by quantifiable measurements rather than by subjective assessments.

K. R. Whittington (*TI Research Laboratories, Hinxton Hall, Hinxton, nr Saffron Walden CB*10 1*RH, U.K.*). I should like to draw attention to a complicating factor in industrial ultrasonic testing which, so far as I am aware, does not occur in medical ultrasonic practice. When an interrogating pulse of ultrasound interacts with a defect in a metal specimen, complicated mode conversions can occur. The most common mode conversions are from transverse to longitudinal waves and vice versa, but conversions to Rayleigh waves, which travel along the defect and then cause reradiation of ultrasound from the defect tip, can also take place. Our own work on Schlieren visualization and computer simulation has shown that even with simple defects, multiple mode conversions take place and as a result up to 14 different pulses can be generated. The amount of energy appearing as exit pulses in various directions arising from these mode conversions can vary greatly with small changes in the angle of approach of the incident wave front. This makes it very important to develop a thorough understanding of defect interactions in industrial applications. In medical ultrasonics, on the other hand, the insonified tissue appears to the interrogating pulses mainly as a fluid medium which will not support shear waves; consequently, these mode changes cannot occur. I should welcome Mr Sharpe's comments.

R. C. Chivers (*Department of Physics, University of Surrey, Guildford GU*2 5*XH, U.K.*). I should like to suggest that the problem in non-destructive testing in which interrogating agents are used is essentially an inverse problem which will not, in general, have a unique solution. The investigation is thus concerned with the probability of a particular chosen solution being an accurate diagnosis. As Mr Sharpe has shown, the diagnosis depends on a number of interrelated factors and presumably as many independent measurements must be made as there are factors to be known in order to raise the level of probability of an accurate diagnosis to a predetermined acceptable level.

R. S. Sharpe. I fully support Professor Brown's plea for more academic training and research in non-destructive testing and I hope this meeting will have served to put this point in better perspective.

My advocacy of ultrasonic holography is based on the fact that we have clearly demonstrated that better resolution can assist in measuring and characterizing defects and provide far more information than is normally available with currently used ultrasonic flaw-detection instrumentation, especially in thick steel sections (up to 25 cm thick). To obtain comparable resolution (λ laterally and 2λ in depth) with a C-scan technique, a focused probe is necessary and optimum resolution is then only achieved in the focal plane. The same probe used for holography will give the same resolution but in any plane required within the range gate used, from a single scan of the specimen. As currently used, the photographically recorded hologram is merely a convenient method of recording phase and amplitude information from ultrasonic wavefronts and the optical reconstruction is then a useful way of automatically carrying out correlation calculations on these recorded data. When fully developed, the alternative use of a digital computer will remove some of the technical limitations arising from the use of an optical bench and should allow considerably more flexibility in processing the accumulated ultrasonic data.

Dr Emerson is right in emphasizing the point that 'quality' of a product is a far less tangible property than merely presence or absence of the defects and other structural discontinuities that one tends to associate with non-destructive testing. Although the presentation had to be abbreviated, my paper does stress the importance of building up research in this area, to back up the many empirical and tentative relations that have been developed to satisfy particular definitions of 'acceptable quality' based on operating experience.

Mr Whittington's comment on problems of mode conversion is particularly relevant to the discussion when one is comparing engineering and medical testing systems. The work of his own group in visualizing and theoretically analysing the complexity of the situations that can arise in tubing has done much to highlight the difficulties and pitfalls in interpretation that mode conversion can introduce in engineering non-destructive testing.

Dr Chivers rightly states that unambiguous diagnosis usually requires analysis of many independent measurements and observations. In engineering practice, however, the academic solution of a multi-variable problem can rarely be properly developed. The search is always for a simple, single measurement that can be carried out by operators with minimum training in the shortest possible time and at lowest possible cost, with minimum disruption to the production or operation of plant or machinery. It is in these circumstances that the purity of science and the exigencies of manufacturing practice have a difficult interface.