Advances in the Technology of Mechanized Ultrasonic Testing [and Discussion]

A. De Sterke and J. Mallard

Phil. Trans. R. Soc. Lond. A 1979 **292**, 207-221
doi: 10.1098/rsta.1979.0055

Phil. Trans. R. Soc. Lond. A. **292**, 207–221 (1979)
Printed in Great Britain

Advances in the technology of mechanized ultrasonic testing

By A. de Sterke
Röntgen Technische Dienst b.v., Delftweg 144, *Rotterdam, the Netherlands*

The detection of flaws in constructional materials by manual ultrasonic scanning has proved its efficiency over more than thirty years. An almost irreplaceable advantage of the manual scanning operation is the flexibility in movement of the ultrasonic search unit. However, disadvantages are the restricted reproducibility and reliability of the results obtained. A further restriction is the human inability to comprehend and correlate the full content of information which the screen images of the ultrasonic testing instrument display. Finally, the relatively low speed at which a manual inspection can be carried out is an important restriction too.

Mechanical ultrasonic testing has overcome several of these difficulties and enables direct readable results to be obtained and storage of data if periodic inspections are envisaged. A number of ultrasonic search units can be used simultaneously and previously programmed with regard to their function, the volume to be tested and sensitivity. The data collected may be evaluated automatically according to built-in criteria.

Introduction

Before entering into the subject of mechanized ultrasonic scanning it would seem useful to indicate a few points of difference in the application of ultrasonics in medical diagnosis and in the ultrasonic testing of metal structures.

Since cross fertilization of ideas is a main aim of this discussion meeting it is important to appreciate that, although the principles applied are the same in both applications, differences exist with regard to: sound velocities, material density, specific acoustical impedances, wave types, the phenomena of mode change, the general shape of the object to be examined and techniques to be used, the character and shape of discontinuities to be detected and evaluated, the coupling conditions, the homogeneity of the materials examined, and the introvert nature of a metal structure compared with a living organism. These differences are shown in figure 1*a*–*f* and will be briefly explained and commented upon.

Sound velocities, material density and specific acoustic impedance

Table 1 shows values for the most relevant media in this context. It should be noted that the velocities of ultrasound in tissue and steel differ by a factor of approximately four. Consequently for a given frequency the wavelength in steel is four times larger. Since the depth resolution of any ultrasonic test-system is determined by the wavelength this puts the application in medical diagnosis in a more favourable position (figure 1*a*). Although an increase in frequency by a factor of four would result in a similar resolution in steel, this is generally impracticable due to the proportional increase of the sound attenuation with frequency.

Another effect of this difference in velocity is the beam profile, since the divergence of the ultrasonic sound beam varies in proportion to the wavelength (figure 2). The ultrasonic beam in tissue tends to be less divergent for a similar size transducer. This improves the lateral resolution which is important in the analysis of signals. On the other hand, in the industrial application of ultrasonic testing one may express some preference for a wider beam-spread as long as the examination is for flaw detection rather than quantitative evaluation of signals, since one would cover a larger volume at one time.

TABLE 1. SOUND VELOCITY, v, DENSITY, ρ, AND SPECIFIC ACOUSTIC IMPEDANCE, i, OF DIFFERENT MEDIA

medium	$v/(10^3\ \mathrm{m\ s^{-1}})$	$\rho/(10^3\ \mathrm{kg\ m^{-3}})$	$i/(10^6\ \mathrm{kg\ m^{-2}\ s^{-1}})$
air	0.33	0.0012	0.0004
water	1.48	1.0	1.48
biological tissue	1.45–1.58	0.95–1.08	1.38–1.70
bone	4.08	1.91	1.38–1.70
perspex	2.73	1.18	3.22
aluminium	6.32	2.70	17.06
steel	5.93	7.70	45.65

WAVE TYPES

Contrary to tissue, metals and other solids can withstand shear stresses. Consequently, shear waves can be generated in metals and used instead of compressional waves (figure 1 *b*). Since their velocity is dominated by the shear modulus of the metal (instead of the Poisson ratio for compressional waves) it is appreciably lower.

The shear wave velocity in steel is 3.23 km $\mathrm{s^{-1}}$ and in aluminium 3.13 km $\mathrm{s^{-1}}$. Comparing it with the values given for the compressional waves in table 1 one observes a ratio of nearly 2. Sometimes the use of shear waves has a particular advantage; however, in other cases they accompany the compressional waves and produce misleading echo indications. For instance, if for some reason it is desirable to transmit sound at an angle into the material one makes use of a sound refracting prism as shown in figure 3. Unless one has passed the critical angle for the compressional waves, two wave types are transmitted with different velocities and directions and it becomes complicated to sort out signals of different origin.

MODE-CHANGE

A similar phenomenon also occurs once sound strikes an interface or boundary of a solid body at an angle. Part of the incident energy may be converted into the other wave type and affect again the interpretation of the echo pattern displayed. Wanted signals from certain reflectors may be lost completely and others, unwanted, may be set up.

GENERAL SHAPE OF OBJECT TO BE EXAMINED

Many industrial products, partly due to design and manufacturing processes, are parallel-sided, for instance rolled plates and sections, and cannot be modelled to suit testing circumstances. However, extensive use is made of this parallelism of bodies to suit the testing procedure as will be briefly explained.

Bottom-echo

If the material is examined with a beam transmitted perpendicularly to the surface, a strong echo from the opposite parallel surface may be expected, normally referred to as bottom-echo.

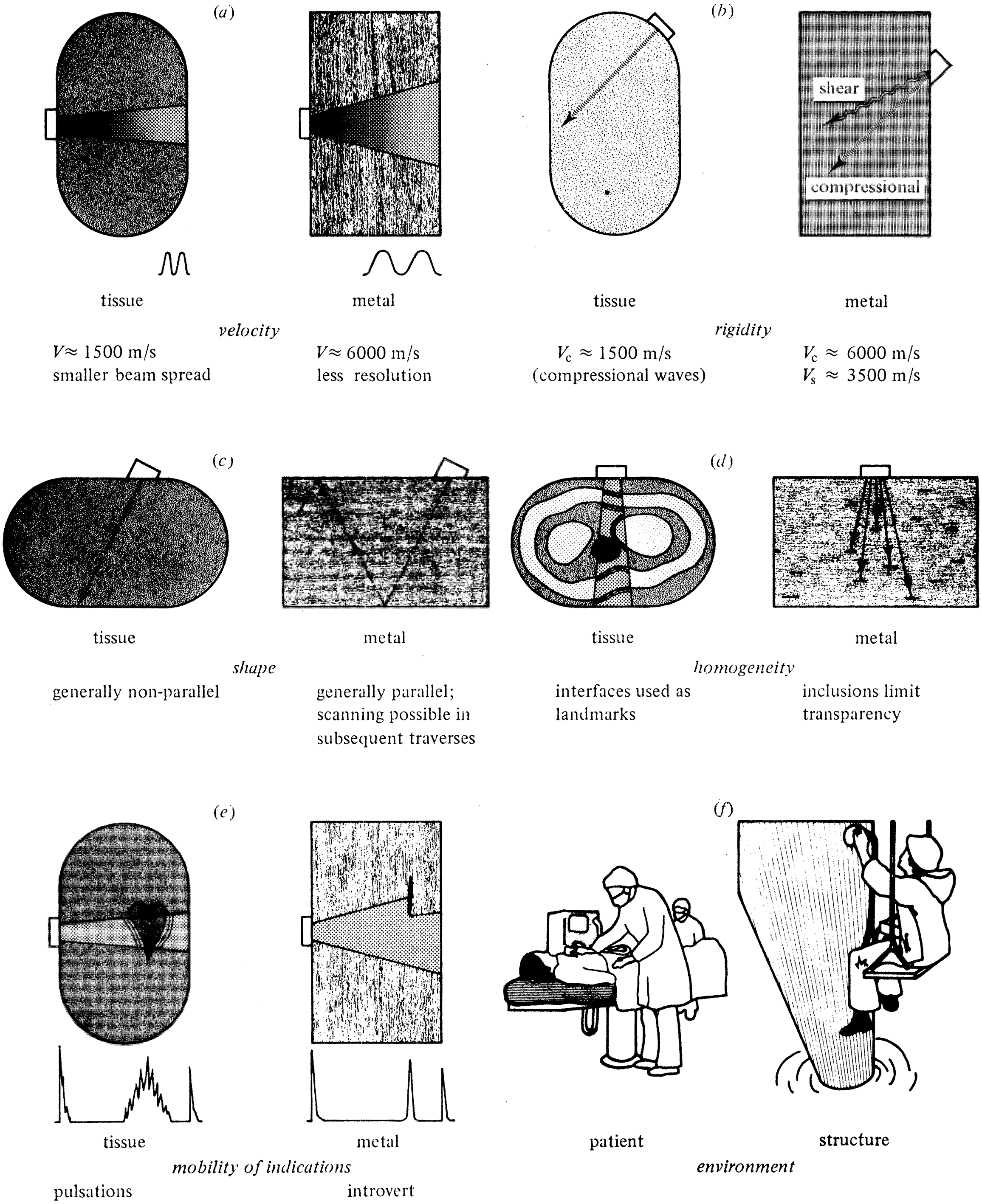


FIGURE 1. Differences between medical diagnosis with ultrasonics and ultrasonic testing of metal structures. (a) Velocity, (b) rigidity, (c) shape, (d) homogeneity, (e) mobility of indications, (f) environment.

This echo is commonly used as a reference to evaluate other signals coming from flaws. It facilitates the adjustment of the sensitivity setting of the ultrasonic instrument to the sound attenuation and sound velocity in the material. Another aspect of parallelism is the possibility of examination in a second or third traverse. These are techniques which are not applicable in medical diagnostics (see figure 1*c*). An example of such a second traverse scanning is found in the examination of welds (figure 4).

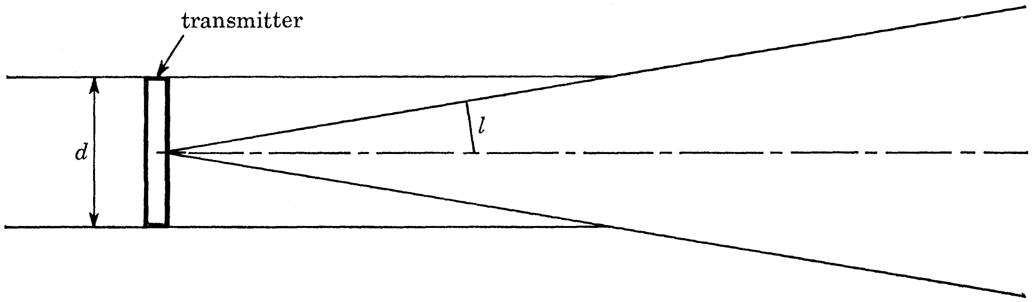


FIGURE 2. Parameters determining beam-spread in far-field: $\sin l = CV/fd$, where V is the velocity in metres per second, f is the frequency in hertz and d is the transducer diameter in millimetres.

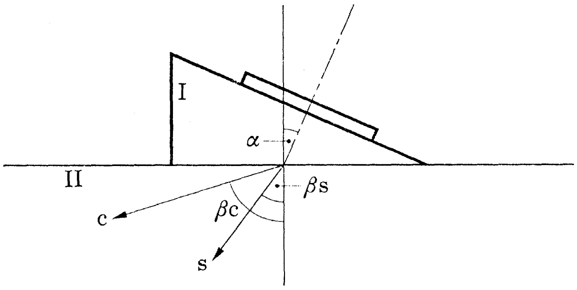


FIGURE 3. Sound refracting prism used in ultrasonic testing of solids to transmit sound at an angle: $\sin\alpha/\sin\beta_c = V_{\mathrm{I}}/V_{\mathrm{II,c}}$; $\sin\alpha/\sin\beta_s = V_{\mathrm{I}}/V_{\mathrm{II,s}}$.

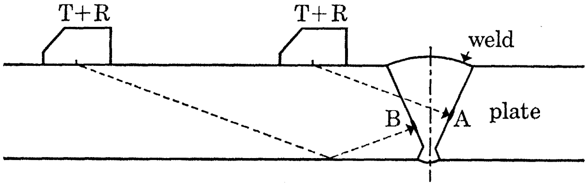


FIGURE 4. Detection of weld flaws by reflected ultrasonic waves transmitted (T) and received (R) in first and second traverse. A, flaw in first traverse; B, flaw in second traverse. Note that there is a beam-spread as indicated in figures 2 and 5. The dotted line only indicates the beam axis.

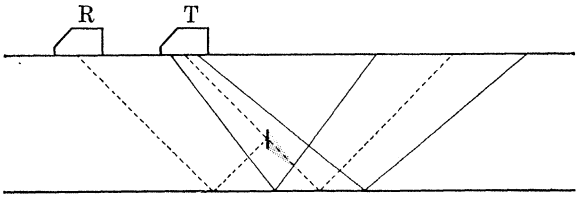


FIGURE 5. Influence of planar flaw perpendicular to surface. Reflected signal bounces away from flaw and requires a separate receiver (R) to be picked up (tandem technique). Transmitted signal loses energy owing to shadow effect of flaw.

Similar techniques are used to test the sound transmission in parallel shaped bodies, for instance to reveal the presence of discontinuities too small to produce signals of sufficient amplitude to exceed the noise level. It may also be used to detect large flaws whose orientation and surface condition is insuitable to produce a direct positive signal (figure 5). A transmission test is normally used to check the efficiency of the acoustic coupling of the probes. Inadequate coupling would be indicated by loss or reduction of the transmitted signal.

Character and shape of discontinuities

In ultrasonic medical diagnosis one is aware of a multitude of interfaces between different biological tissues. The majority of these interfaces produce signals which can be used as landmarks for analysis (figure 1*c*). The variations in the specific acoustic impedance of different tissues is large enough to cause reflexion, but generally not too large to prevent sound transmission. In the examination of metals the contrary applies. The specific acoustic impedance of steel compared with that of inclusions or gas in the case of cavities or cracks is such that nearly complete reflexion takes place, unless such inclusions are present in the form of a very thin layer and become more or less transparent. They are not used as landmarks. The echoes from the surfaces of the object are used for this purpose. Location of flaws depends on correct calibration of the time base of the instrument and knowledge of the position of the beam-index (the point where the beam centre intersects the scanning surface of the workpiece). Since the physical dimensions of the test object and its sound velocity are known, one indeed needs no landmarks and often attention can be focused on a well defined part of the time base to reveal flaws in a suspected volume. In mechanized testing an electronic gate can be used to concentrate attention on the region of interest.

A particular phenomenon of reflectors is that they behave like elementary sound transmitters once struck by an impinging sound wave. The divergency of the reflected signal decreases with their size in the same way as indicated in figure 2. As long as such reflectors can be hit perpendicularly, their detection is evident. However, deviations from this angle strongly influence the amplitude of the signal received.

Several conclusions may be drawn:

(1) The application of tandem techniques as indicated in figure 5 is essential if large smooth flaws lying perpendicularly to the surface are expected.

(2) The criticality unfortunately increases with flaw size.

(3) In flaw detection procedures one relies upon the response of favourably orientated facets.

(4) The amplitude of a flaw echo has no bearing on flaw size unless its orientation to the beam axis is well known.

The quantitative evaluation of flaws on the basis of echo size alone is therefore only possible in exceptional cases.

Coupling conditions

The acoustic coupling of an ultrasonic transducer to a metal surface is generally accomplished with water or oil. The surface condition has a great effect on the coupling efficiency and contrary to the situation in medical ultrasonic testing, the surface cannot simply be 'shaped' to the transducer by a moderate pressure on the probe.

Although the liquids mentioned may fill unwanted grooves and large pits under the probe, they cannot prevent the refraction which diverts the sound beam from its intended direction. Therefore metal surfaces should be prepared before the examination so that they are smooth. In mechanized scanning, probe systems are generally acoustically coupled to the object by running water.

The homogeneity of the material

Although in medical diagnostics one has learned to live with inherent discontinuities in the medium to be examined and even make use of them for identification purposes, application of ultrasonic testing to metals relies very much on the fact that such crystalline materials are reasonably homogeneous and isotropic. If this condition is not fulfilled, owing to dispersed inclusions or anisotropic structures, difficulties arise. In particular, austenitic stainless steels and similar materials used in corrosive environments have a strong tendency to scatter sound waves.

This makes the examination of welds having a coarser grain structure than the rolled material problematic. Still much work must be done, both from the metallurgical as well as from the testing side, to improve this situation and to achieve the level of flaw detectability one is used to in the examination of normal ferritic steels.

The introvert nature of non-biological structures

Pulsations in living tissue can be recorded during the application of ultrasonic testing in medical diagnosis. In this way the structure under examination clearly helps to identify particular signals and the interpretation of images obtained (figure 1*e*). However, in the ultrasonic pattern displayed in the examination of metal structures, the images are frozen as long as the relative positions between probe (or probes) and object surfaces are steady, unless external stresses are applied, for instance during a fatigue test of specimen. Although a relative movement of the probe sometimes helps to make small signals visible between irrelevant noise signals, this has so far not developed into a practical technique and generally such probe movements are only related to mechanized scanning. Nevertheless, material flaws will not really change their response unless looked at from various directions. Such techniques are applied in the evaluation process mainly to determine the directionality of such flaws and add to the information required.

Weld testing

Over many years, mechanization of ultrasonic testing (sometimes referred to as automation) has been developed in several industries. Capital investments have been made in the aircraft and steelmaking industries to inspect their products, as well as in the application to railways for periodic inspection of rails (Martin & Werner 1956). In the concept of the present meeting the considerations will be concentrated upon the ultrasonic testing of welds. Weld testing has been for a long time the exclusive domain of radiography; however, during the last 20 years there has been a growing interest in ultrasonic weld testing (Welding Institute 1977). One of the limiting factors to its general acceptance has been the subjective nature of manual ultrasonic test reports. To appreciate the influences involved it may be useful to summarize the operations leading to the final test report. Ultrasonic testing can be subdivided into the following three phases (figure 6): detection, characterization or identification, evaluation or sizing.

Generally these operations are merged and carried out by one operator. Sometimes final evaluation and sizing are carried out or supervised by a higher level technician. In his search for defects the operator moves the ultrasonic probe or probes according to a prescribed zig-zag pattern, along the weld (figure 7), whereby the echo pattern is displayed in an A-scope presentation on the test instrument. From the screen image he notes travelling time of flaw echoes, their amplitude and shape. The techniques applied are not relevant to this dicussion; however, they can be derived from the previous explanations given and the indications in figures 4 and 5.

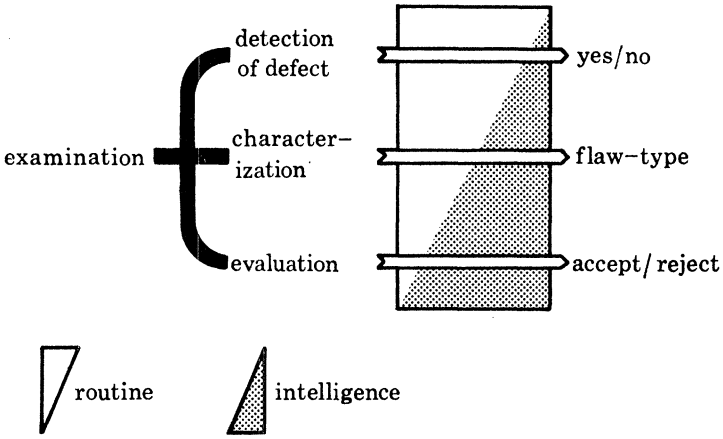


Figure 6. Phases of examination. Routine and mental efforts required are given in simplified form.

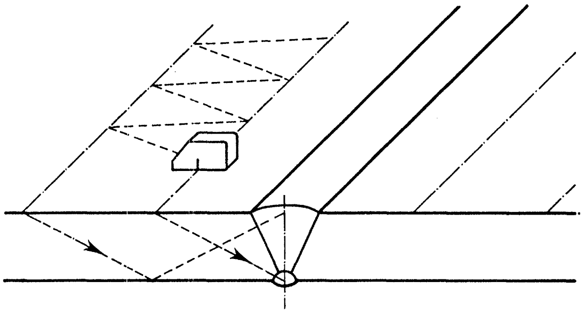


Figure 7. Zig-zag pattern to be followed by a manual scan to reveal weld flaws: close to weld for detection of root defects; away from weld for examination of upper zone; intermediate positions to cover entire weld height.

The beam-spread, useful in flaw detection, is a drawback during subsequent analysis of flaws. It would indeed be advantageous to have a pencil-like beam for the determination of the contours of the reflectors found. Although focusing probes are available, they do not belong to the normal outfit of an operator and a range of these probes would be required to cover a range of distances, since they may only be used at their characteristic focal length (Wüstenberg *et al.* 1977).

The analysis of flaws requires sufficient knowledge of welding techniques in general and more particularly of the welding process employed and weld shape achieved. The operator takes into account the apparent location of the flaw, its reflecting properties and estimated size to characterize the nature of the flaw. A further evaluation includes a more accurate size estimation which is mainly based on amplitude measurement and flaw contour determination. These operations can still be regarded as rather primitive and lack the accuracy of resolution one is used to in radiography. Furthermore, they must generally be carried out in an environment which is far from clinical. Site conditions frequently have an unfavourable influence on the operator's attention and accuracy (figure 1*f*). In this respect it should be noted that the understanding of patterns related to a particular flaw seen from different angles and distances is more than one may normally expect from an ultrasonic operator. There is a remarkable contrast in the level of intelligence required to draw on the basis of A-screen presentations a three dimensional picture of flaws for such an analysis and the rather boring probe manipulations the operator is forced to perform during his initial search for defects. Nevertheless, ultrasonic weld testing has been increasingly applied during the last 20 years mainly because of its inherent good sensitivity in the detection of harmful two-dimensional (planar) defects.

To reduce the shortcomings of manual ultrasonic scanning, tests may be repeated by several operators. This system is adopted by several authorities for the examination of welds in nuclear pressure vessels. The examinations are carried out three times in succession by different operators and their combined results are analysed. Needless to say, this is a very time-consuming operation.

Mechanized testing

From the foregoing it can be deduced that an important incentive for mechanization of ultrasonic testing is to improve reliability and to collect all data relevant to a quantitative analysis of the results in an efficient way (de Sterke 1977).

Mechanization is necessary if remote handling of probes is required, for instance in a radioactive environment as is the case in periodic inspections of nuclear installations. Underwater examinations sometimes require remote operation, and scanning of welds during the fabrication process is an example whereby remote probe handling is dictated by the temperature.

Speed of examination is an important incentive too, particularly if feedback of information is envisaged in a mass production process to rectify possible errors in the parameters or in periodic inspections of capital intensive installations to reduce outage times. However, there is no need for speed in connection with real time imaging which is such an important inducement in medical applications. In summary, the main advantages of mechanized testing are greater reliability, better reproducibility, direct recording potential, increased speed, and remote operation.

Multiple probe systems

Multicrystal probes used in linear array or phased array systems for medical applications are basically intended for high speed beam movement (Ligtvoet *et al.* 1977). Multiple probe systems for industrial applications, although the individual crystals may be housed in one probe, have a different function. The subsequent activation of the transmitting elements takes place at the relatively long intervals of 20 ms. Instead of creating a cooperative function in beam-formation these intervals are long enough to avoid completely interference of signals and so-called ghost echoes. Actually, the distance between two subsequent wave-trains transmitted by adjacent probes may be as long as an equivalent of 200 cm in steel.

The activation is accomplished by a multiplexing system normally operating at 2–5 kHz. The use of a multiple probe arrangement in an industrial application can be better compared with tomography. Welds to be examined are divided into a number of zones parallel to the material surfaces. Each probe on its own or in combination with a partner probe serves the function of detecting and analysing flaws in a particular zone. In the example shown in figure 8, eleven probes are used to examine the five zones which subdivide the thickness. All probes are used in a transmitter–receiver function to search for inclined defects. Probes operate also jointly, one as a transmitter, the other as a receiver to detect flaws whose main direction is perpendicular to the outer surfaces, or work together in a separate transmitter–receiver function to check the sound transmission. All of these separate probes need to be programmed in accordance with these functions. The number of probes used depends on the material thickness and accuracy of location required.

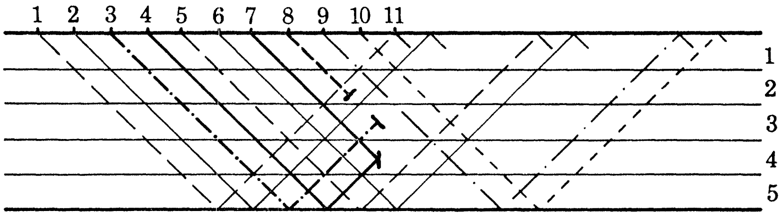


FIGURE 8. If no flaws are present, pulses follow their zig-zag path uninterrupted as for pulses transmitted from probes 1, 2, 5, 6, 9 and 10. Once a perpendicular flaw is present as in zone 4, the probe combination 4–7 will detect the reflexion (tandem system). Reflected pulses from inclined flaw as in zone 2 will be detected by probe 8 and in zone 3 by probe 3. The probes then work according to a single probe operation. Sound transmission can be checked by the combination of probes 1 and 11.

Such multiple probe systems are used for the examination of nuclear pressure vessels (de Raad & Engl 1975). An example is shown in figure 9. Here a set of eight probes is being set up in a dry run, before the operation of the installation. Should the entire material volume of the cylindrical part of the vessel wall need to be examined, a screen pattern is followed along the surface. A certain overlap of the beams would always be necessary to obtain complete coverage of the volume; however, one would generally agree upon certain tolerances in detection sensitivity. Normally this pattern will be based on a -6 dB beam boundary.

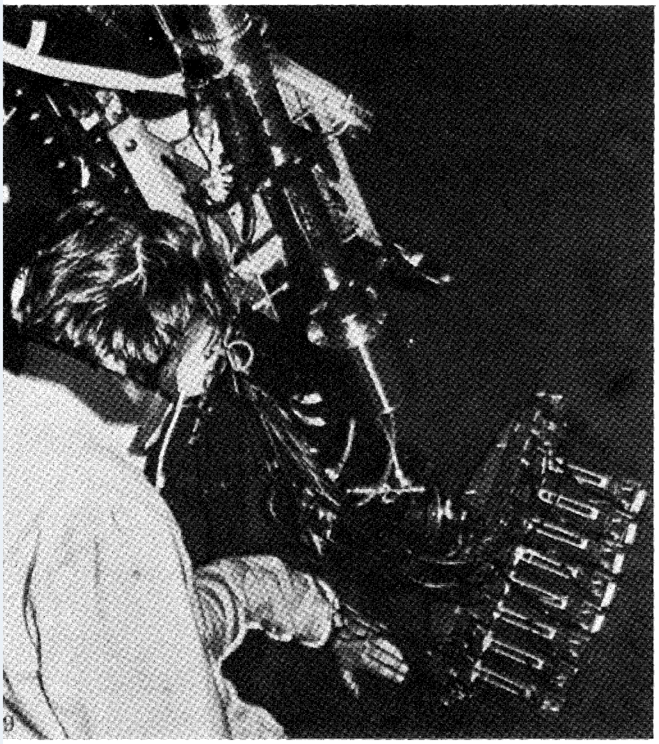
A more efficient beam shape can be obtained by fitting the probes with a number of crystals. In fact it would not be impossible to adapt the linear array system used in medical applications to improve the effective beam width even further. However, one should be aware of the limiting factors with regard to testing speed, once such large volumes as a reactor pressure vessel wall are involved. A scanning path of 15 km is in this case realistic.

Similar systems have been developed for the examination during the manufacturing stage of the vessel.

ANOTHER EXAMPLE OF MECHANIZED ULTRASONIC TESTING

In pipeline constructions, automatic test systems have been used for many years to examine the longitudinal welds. Compared with the pressure vessels mentioned above, the wall thickness of linepipe is rather small and no subdivision in zones over the thickness is normally applied. However, for thicknesses over 12 mm it would be both sensible and possible. For offshore pipelines, generally greater thicknesses are employed and an effective examination is very desirable to maintain the quality required to withstand the laying and buckling stresses (Mercer 1976). Mechanized ultrasonic equipment recently developed for this purpose is shown in figure 10. Depending on the system of welding used on the lay-barge, only a few minutes are available for inspection and mechanized ultrasonic testing would be a very useful substitute for weld-radiography which is the current method in use (de Sterke 1975).

The principle of the scanning system is shown in figure 11. However, four of these multiple crystal probes, two sets diametrically positioned on the pipe, are used. They are rotated over 190° of the circumference. A direct readable ultrasonic record of the weld condition can be obtained in the very limited time available. Less than 1 min scanning time is required to examine a weld in a 36 inch (90 cm) diameter pipe. The findings can be shown according to figure 12 in a so-called 'go–no-go' fashion with a 20 channel event recorder.



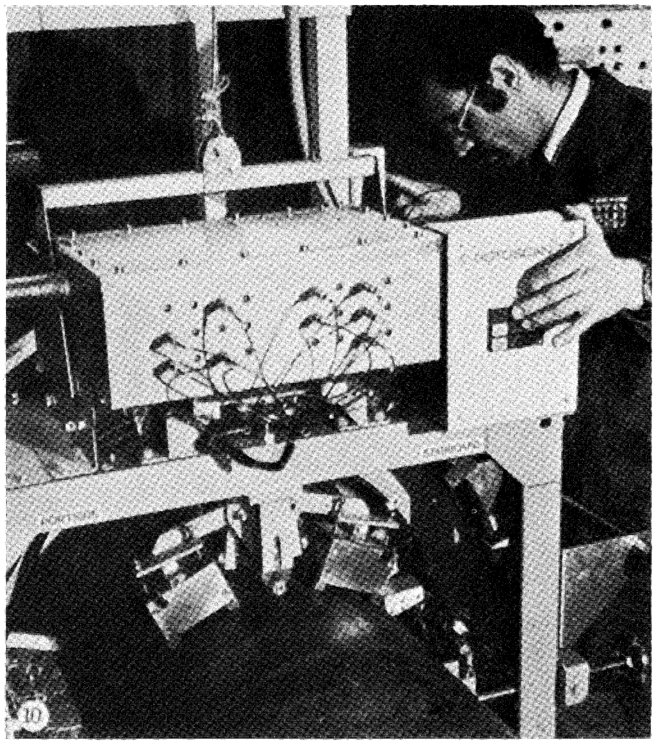


Figure 9. Multiple probe system being mounted at the spin end of a manipulator to examine the lower part of a nuclear pressure vessel before the installation is used. In this way a baseline document can be made to serve as a reference for subsequent remote controlled periodic inspection. Before the examination the vessel will be filled with water for immersed scanning.

Figure 10. Mechanized ultrasonic equipment for examination of circular welds aboard a lay-barge for offshore pipelines. Several multicrystal probes can be rotated around the pipe to obtain direct record of all significant flaws at the speed of the welding operation. Scanning time for a 30 inch (73 cm) diameter weld is 45 s.

Data recording

Several ways of data recording are applied in mechanized ultrasonic testing techniques. Rarely, visualization takes place in the form of geometric flaw pattern or presentations similar to those used in medical practices. Only in the testing of relatively small objects are fascimile recorders sometimes applied.

For periodic inspections of nuclear pressure vessels it is not unusual to store data on magnetic tape and produce hard copies of data referring to a particular material volume via an oscilloscope display or with multichannel pen recorders.

For mechanized testing of welds during the fabrication stage it is advantageous to make online records for direct evaluation of flaws detected. Such records can be made according to similar principles as shown in figure 12, but with more than one recording level. The record, as a certificate of examination, may also contain a direct plot of component data and equipment setting as stored in its electronic memory, namely a first level for 'good workmanship' and a second level which could be based on 'fitness for purpose'. Such levels may be set for each channel individually, depending on the particular scanning mode and flaw depth they refer to. They reflect the intentions of acceptance codes and contain printed data relevant to component identification and equipment setting.

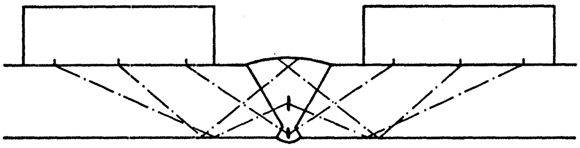


FIGURE 11. Multiple transducers are used to scan pipeline welds from several directions simultaneously. Weld height is divided into zones: root zone, middle zone and top zone, and weld width in left and right halves. A multiple gating system is used to address possible flaws according to their location once they exceed a predetermined level of reflectivity. Acoustic coupling and transparency is checked by signal transmission between the two probes. More of these probe sets are found along the pipe circumference.

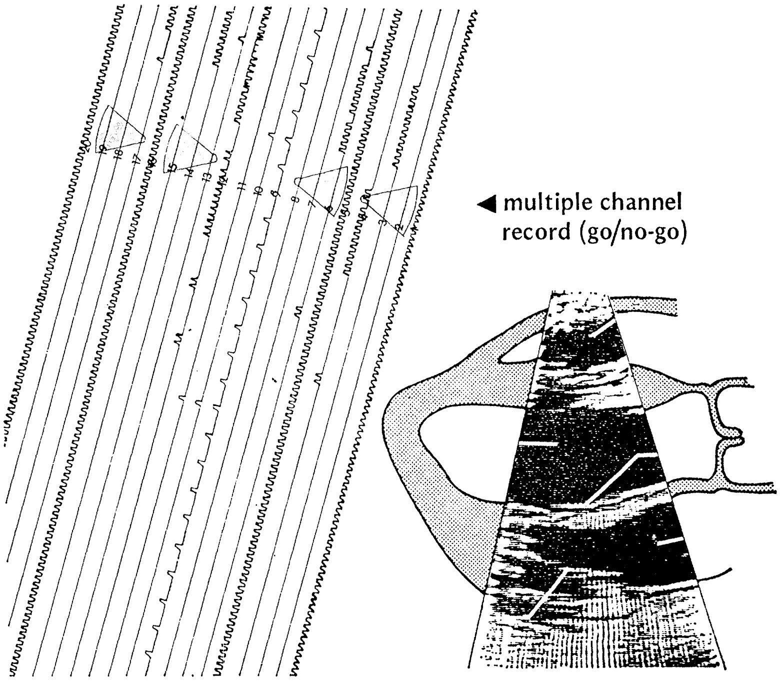


FIGURE 12. Comparison of recording used in medical diagnosis (*b*) (right) for direct visualization of acoustic reflexion pattern in echo-cardiology (Henry & Griffith 1977) and multichannel record (*a*) of pipe weld indicating position of defects in three dimensions and their length. In the present case 12 channels are used to reveal all flaws exceeding a prescribed reflectivity level. Four of the channels maintain a continuous check on the acoustic coupling of the probes. One trace produces an overall record and indicates any deviation found, either flaw reflexion or lack of transmission, no matter which probe or crystal it refers to. The remaining three channels are used to mark position and length of flaws found (1, 10 and 50 cm scale).

IMPLICATIONS OF CODE REQUIREMENTS

Except for welds in heavy sections, acceptance codes for weld defects are largely based on the results obtained with radiography. Although such codes permit ultrasonic inspection as a tool in quality control, they still require that defects found ultrasonically are subject to further investigation and final acceptance on the basis of radiography.

In so far as the acceptance criteria are closely related to the nature of defects present this seems very reasonable. Nevertheless it must be appreciated that, if the radiograph does not disclose a defect apparently present according to the ultrasonic test result, the nature of the defect may be crack-like and be undetectable by radiography. In this case final judgement could better be based on the ultrasonic findings.

Another difficult situation is found if a code permits, within certain limits of length, a planar defect like lack of fusion, but does not allow the presence of any crack irrespective of length. Rejection of cracks regardless of their length as seen on the radiograph may be sound practice as such an indication suggests that some basic problem may exist and secondly the crack due its nature may be twisted and only partly shown on the radiograph. In fact the crack may be much longer than indicated and its depth greater than can be estimated from a radiograph. On the basis of such philosophies the acceptance criteria for ultrasonic testing (particularly mechanized ultrasonic testing) should be reconsidered, recognizing the reality that ultrasonic examination is better able to reveal the presence of planar defects like cracks in which our colleagues in the fracture mechanics field are so interested.

Moreover, ultrasonics will not only detect planar flaws with much greater probability but also quantify them more realistically according to their dimensions in depth and length. This is not to say that ultrasonic testing needs no further improvement; on the contrary, it still has far to go. With present-day ultrasonic techniques the resolution is still inadequate to define the nature, shape and distribution of flaws with a precision similar to radiography and although this drawback is largely compensated in practice by the greater certainty that the planar defects that are likely to be detrimental to a structure will be found, further improvements are needed.

FURTHER REQUIREMENTS AND TRENDS

To improve the definition of ultrasonic test results, developments such as ultrasonic holography and pulse analysis systems are proceeding in several laboratories. In the context of mechanized ultrasonic scanning systems it is possible that improvement of resolution may be obtained by the use of higher frequencies, short-duration pulses, improved gating systems, focused beams, or a combination of these.

Limits to these options may be set by the material attenuation as far as the increase of frequency is concerned. This can be partly compensated for by application of travelling time controlled amplification.

With present-day electronic gating, a precision of steel-equivalent of 0.2 mm for shear waves can already be obtained. Application of multiple gating systems may therefore be considered for the improvement of depth resolution.

As far as the lateral resolution is concerned the use of focused beams may be further developed. To compensate for the increase of scanning time, it is worth considering that focusing is only desirable at the locations where flaws are found and that some kind of reflexion controlled beam aperture may be developed. In this respect one may probably take advantage of phased array transducers as already in use in medical diagnosis (Henry & Griffith 1977).

There is a clear trend in the use of mechanized ultrasonics for monitoring capital intensive or critical installations for the initiation and propagation of cracks. Examples are found in those structures mentioned, namely nuclear installations, pipelines and offshore structures.

Ultrasonic mechanized scanning systems will be increasingly used on a larger variety of structures to reduce unforeseen maintenance and to add to their reliability and safety.

REFERENCES (de Sterke)

Henry, W. L. & Griffith, J. M. 1977 In *Echocardiology with Doppler applications and real time imaging* (ed. N. Bom), pp. 51–60. Rotterdam: Martinus Nijhoff Medical Division.

Ligtvoet, C. M., Ridder, J., Lancée, C. T., Hagemeijer, F. & Vletter, W. B. 1977 In *Echocardiology with Doppler applications and real time imaging* (ed. N. Bom), pp. 313–323. Rotterdam: Martinus Nijhoff Medical Division.

Martin, E. & Werner, K. 1956 *Eisenbtech. Rdsch.* **5**, 487–505.

Mercer, W. L. 1976 *Phil. Trans. R. Soc. Lond.* A **282**, 41–51.

de Raad, J. A. & Engl, G. 1975 In *Proc.* 10*th Symp. on N.D.E.*, April 1975, pp. 112–128. San Antonio, Texas: S.W.R.I.

de Sterke, A. 1975 *Br. J. non-destr. Test.* **17**, 102–108.

de Sterke, A. 1977 *Weld. Metal Fabric.* **45**, 215–224.

The Welding Institute 1977 *Handbook on the Ultrasonic Examination of Welds.*

Wüstenberg, H., Just, T., Möhrle, W. & Kutzner, J. 1977 *Materialprüfung* **7**, 246–251.

Discussion

J. MALLARD (*Department of Bio-medical Physics and Bio-engineering, University of Aberdeen, U.K.*). Mr de Sterke mentioned that the multi-detector devices have less resolution than other devices. How is this shown? How is the spatial resolution of his devices measured?

A. DE STERKE. The resolution of a multi-detector device as described in the paper is determined by three factors: (*a*) the characteristics of the individual units; (*b*) the number of zones adopted for the particular material thickness; (*c*) the scanning mode (single probe system, tandem system).

(*a*) The normal parameters (pulse length, beam spread, beam profile) are of importance.

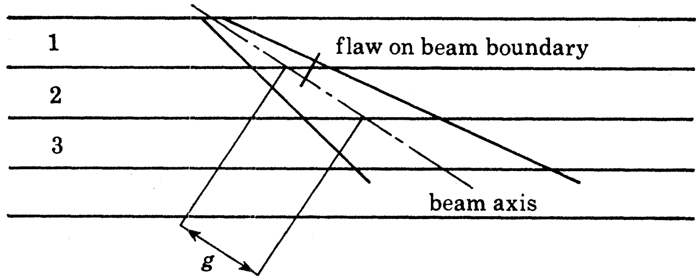


FIGURE 13.

(*b*) The principle of the application of zones is indicated in figure 8. In this case only five zones are drawn. In practice it may be an appreciably larger number (n). However, in this situation the resolution will never be better than the thickness of the zone and hence $n^{-1} \times$ (thickness of material). In fact it can be worse, depending on the orientation of flaws. This is illustrated in the figure 13, where g is the gated travelling path for recording. The flaw in zone 1, provided it is struck favourably by part of the sound in the beam boundary, will be wrongly placed in zone 2 as the pulse travelling time lies within the gated travelling path for recording.

This inaccuracy depends on beam spread, which is determined by the overlap of beams required to ensure sufficient coverage and is therefore inversely proportional to the number of zones selected. The resolution could indeed be improved by increasing the number of zones. It is possible to place a number of subsequent gates per zone to improve the resolution along the beam axis (depth resolution) as far as the application of a single probe system is concerned. This can also be achieved by measurements of absolute travelling time with crystal controlled measuring devices. Depth resolution is then dominated by factor (*a*).

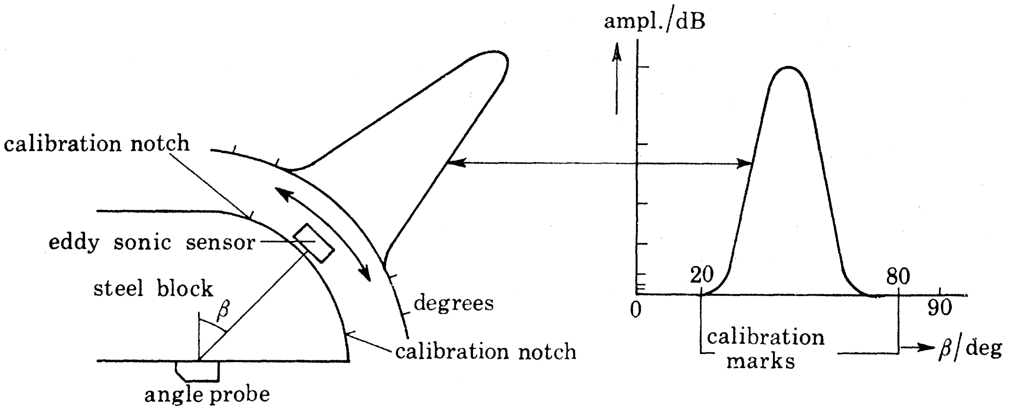


FIGURE 14.

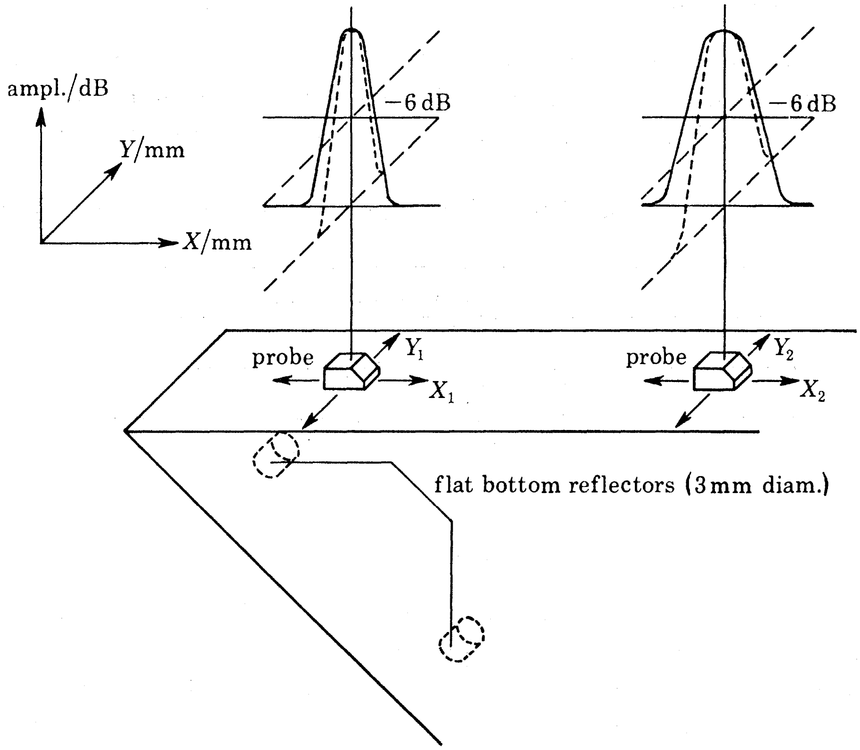


FIGURE 15.

(*c*) The use of multiple gates brings no improvement for the applications of the tandem system since from considerations of the geometry, it follows that all travelling times are equal. Resolution is then determined by the number of tandem systems per multi-detector device, consequently by the number of probes.

Several factors determine how many probes can be applied. Available surface area is one factor, since the minimum size of probes is determined by the allowable beam spread. In this respect the multi-detector devices described differ from those used in linear array systems, where the elements are not working as individual devices but jointly determine beam formation.

With regard to the determination of spatial resolution, three measurements are carried out:

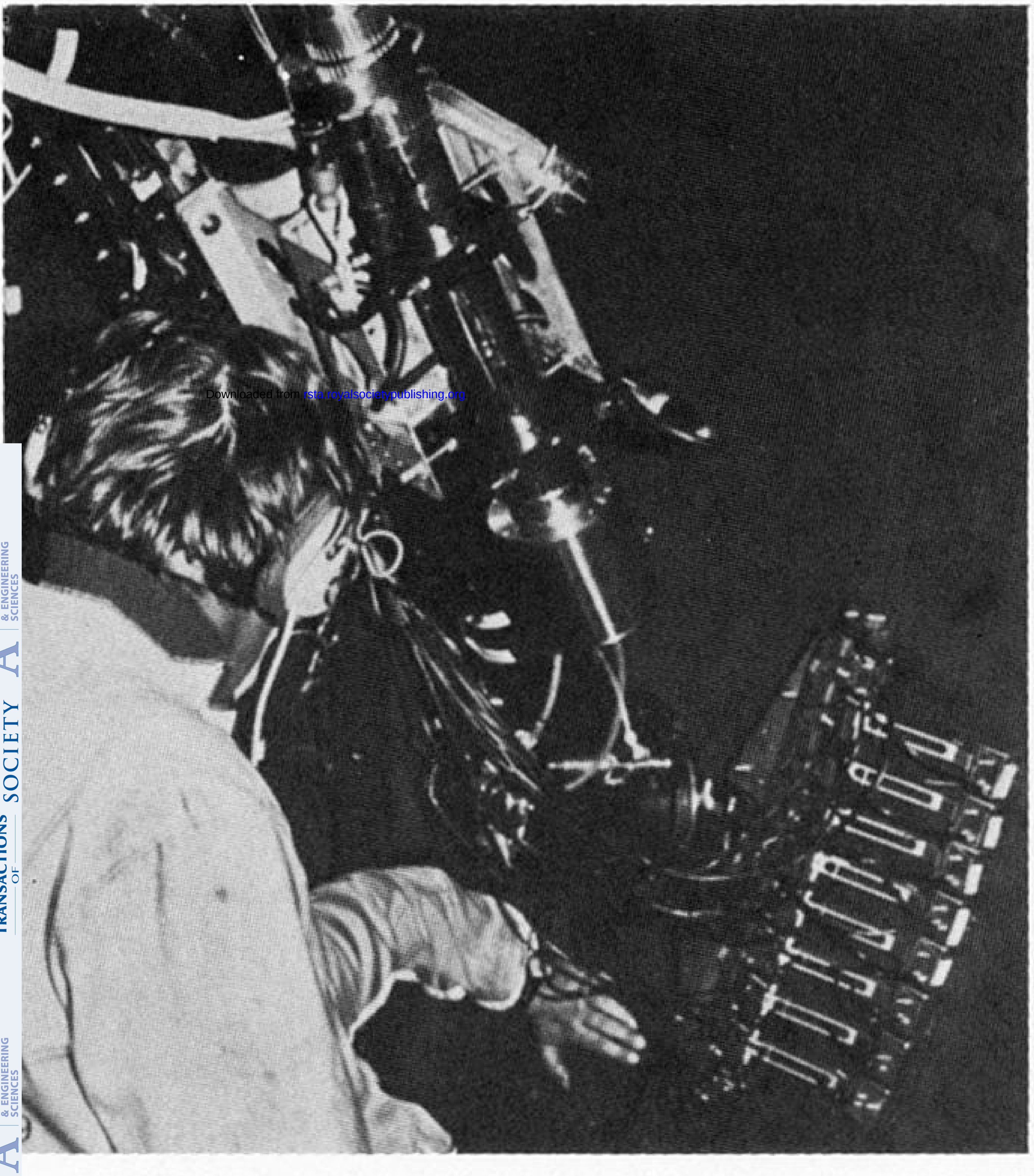
(i) The common determination of depth resolution by closely separated targets either in solids or liquids.

(ii) The determination of beam profile on a metal calibration block with an electrodynamic element by using so-called eddy sonics (Wüstenberg 1972). This produces beam profiles as shown in figure 14.

(iii) The determination of beam profile at different travelling paths (figure 15).

Reference

Wüstenberg, H. 1972 Thesis, Berlin.



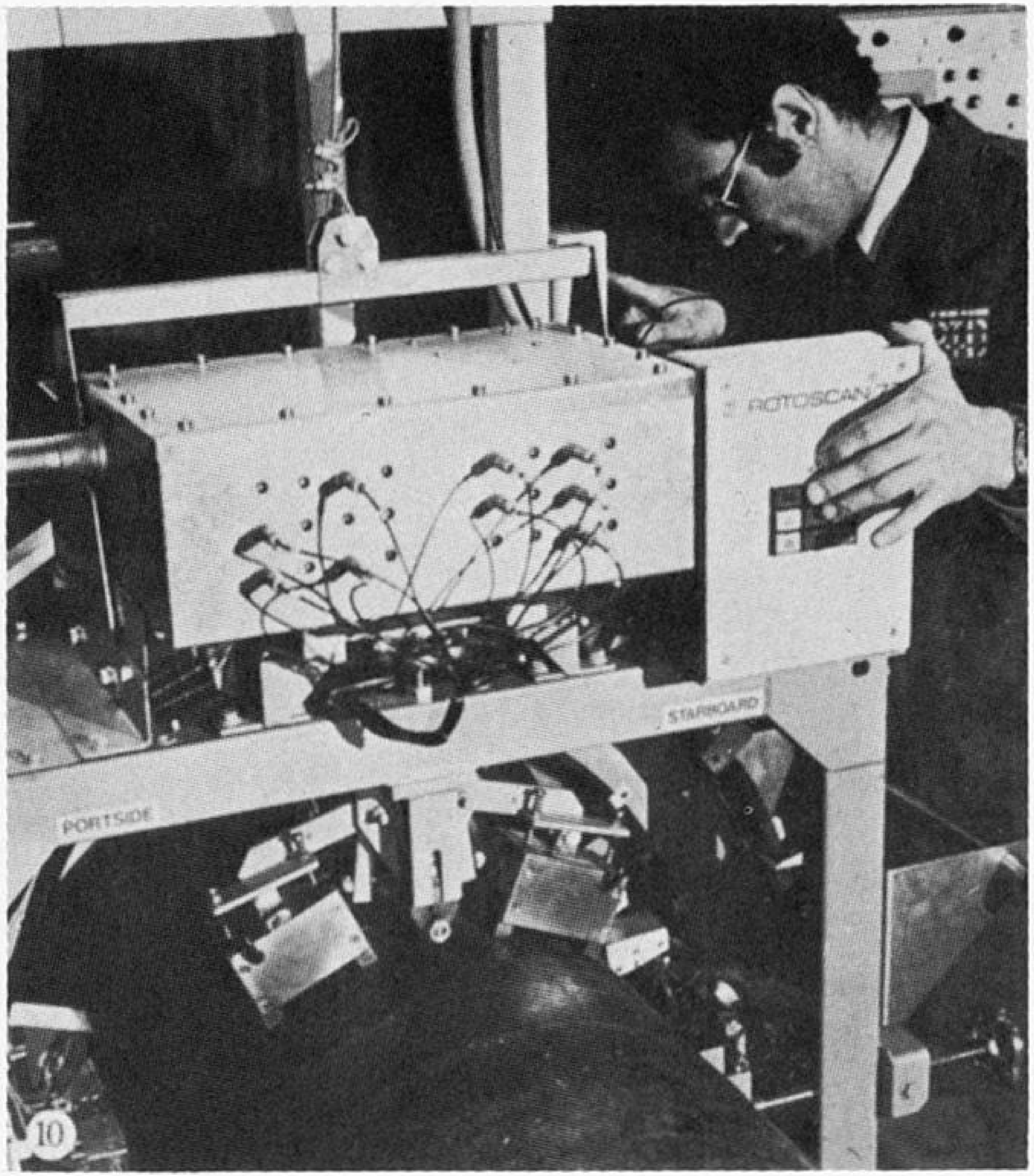


Figure 9. Multiple probe system being mounted at the spin end of a manipulator to examine the lower part of a nuclear pressure vessel before the installation is used. In this way a baseline document can be made to serve as a reference for subsequent remote controlled periodic inspection. Before the examination the vessel will be filled with water for immersed scanning.

Figure 10. Mechanized ultrasonic equipment for examination of circular welds aboard a lay-barge for offshore pipelines. Several multicrystal probes can be rotated around the pipe to obtain direct record of all significant flaws at the speed of the welding operation. Scanning time for a 30 inch (73 cm) diameter weld is 45 s.