Non-destructive evaluation –

challenges and solutions

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This paper, presented by Professor Luísa Quintino at the 60th annual conference of the SAIW, outlines four advanced ultrasonic techniques: ToFD, EMAT, Guided Waves and Phased Array, which provide solutions for four different inspection challenges.

In the last two decades the evolution that has occurred in structural integrity and fracture mechanics calculations has led to a new way of managing plant, which is based on risk analysis and remaining life assessment. This allows the useful life of a plant to be extended, in profitable and safe conditions, well beyond initial equipment design.

As a consequence, non-destructive evaluation (NDE) methods had to be improved in order to cope with risk assessment requirements. The detection capability, accurate flaw sizing and inspection speed demands were set very high. Conventional methods such as Penetrant, Magnetic, Radiographic and Ultrasonic testing were no longer able to provide such results by themselves, leading to the need for other methods or techniques to cope with risk-based inspection (RBI) requirements – fundamental to sustaining the safe development of the industry.

New NDE technologies have recently become important tools for the industry. The present paper presents four advanced ultrasonic techniques: ToFD, EMAT, Guided Waves and Phased Array, each providing solutions for different inspection challenges.

In order to increase productivity, the time required for inspections needs to be substantially reduced, so as to have shorter shutdowns and consequently save costs. To avoid increasing manpower, this can only be done with better shutdown organisation, decreasing the time required for inspection, automation and on-line systems that continuously survey critical components to increase the reliability of NDE.

Remaining life assessment relies on fracture mechanics calculations to predict time to failure and to provide data for plant operation until the next planned shutdown. For effective assessment and prediction of the behaviour of inspected components, so as to avoid unexpected shutdowns, the data used needs to have a high Probability of Detection (PoD), characterisation and sizing of existing discontinuities [1].

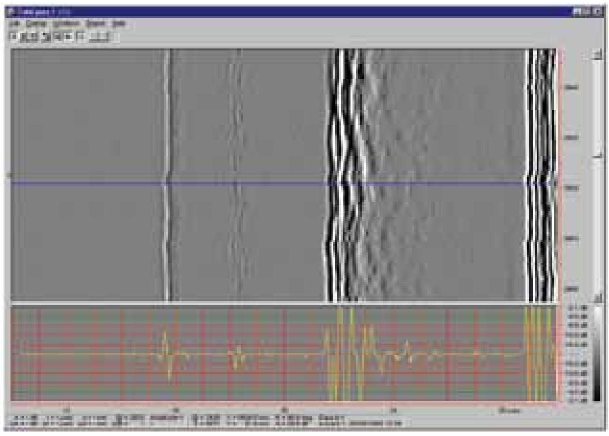
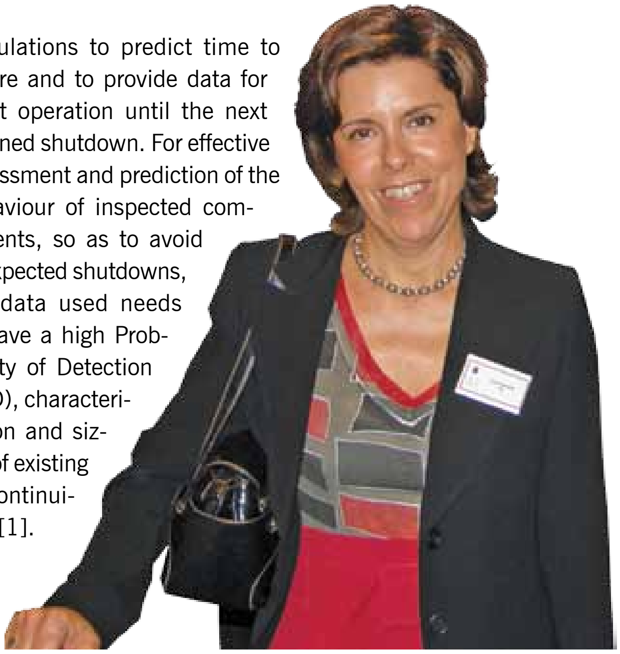


Figure 1: Typical ToFD image, presenting a discontinuity along the weld that was not detected with RT.



Professor Luísa Quintino.

For the managers, the cost reduction is, perhaps, the most important rule of the market, provided that the quality and reliability of components is assured. This can only be achieved through improved NDE techniques – a challenge for engineers and researchers.

NDE is one of the most important diagnostic tools used for remaining life assessment. However, because of the limitations in detection and defect sizing of the different techniques, a correct selection of the best technique or combination of techniques is needed in order to achieve accurate fracture mechanics results. To increase this accuracy, as well as to reduce the time spent in inspection, automation, new techniques, and the extended use of computer-based technologies play an important role.

In maintenance and construction inspection, the Ultrasonic Testing (UT) tool is often used. This method can detect and size discontinuities in the volume of a material. Other conventional NDT methods, like Magnetic Particle (MT) and Penetrant Testing (PT) can only detect surface and subsurface discontinuities with a high PoD, but give no information about size or depth. Methods like Radiographic Testing (RT) can detect and size discontinuities embedded in the inspected volume, but the information about the position in the depth or about the height of the discontinuities is very poor (in conventional RT testing) and its sensitivity to planar discontinuities is low compared with UT.

Recent UT techniques such as ToFD, EMAT, Guided Waves and Phased Array, on the other hand, allow a large amount of data storage, improved sizing accuracy and clear graphic reporting. For monitoring purposes, they can track the evolution of existing discontinuities more accurately by reproducing results in subsequent examinations using the same equipment settings.

ISQ has carried out some recent works in several plants (power, refineries, petrochemical, etc) all over the world, applying the most recent ultrasonic techniques as diagnostic tools to inspect plant components such as pipelines, storage vessels, boilers and reactors both for construction and maintenance.

In this paper, some relevant results achieved by applying the above mentioned techniques in field inspections will be outlined. Each technique will be briefly presented initially in its basic concepts, main characteristics, limitations and advantages, followed by a real on-site example. Finally, a summary table is presented showing the benefits obtained from the application of each particular technique.

Time of Flight Diffraction (ToFD) inspection

The ToFD technique appeared in the 70s when Dr Maurice Silk developed a new form of interpretation of the sound signals that cross the interior of materials. This technique takes into consideration the time that a signal takes to travel from a transmitter to a receiver transducer, particularly those diffracted at the edge of discontinuities embedded in the material.

ToFD was initially developed to size discontinuities but it has now been expanded to include defect detection. The method is based on the analysis of the time that signals diffracted at the extremities of discontinuities need to cover the distance from a set of transmitters to a set of receiver probes, as compared to the time of a surface wave. These signals, and the associated time calculations, will locate, with high accuracy, the diffracted edges of the discontinuities.

The measurements made with the ToFD technique do not depend on the amplitude of reflected signals or any of the factors that affect conventional ultrasonics. There is, therefore, a significant advantage of ToFD over UT.

Basic principles: In order to determine the position of the extremities of the discontinuities, a transmittal wide beam probe is located at one side of the weld tested. An identical receiving probe is located on the other side of the weld. In welds with minor acoustic discontinuities, the first ultrasonic signals are related to the shorter path between the probes that transmits and receives, so called lateral waves. This is followed by reflection of the back wall echo.

If however, there is a discontinuity, the ultrasonic waves will diffract at its edges and the depth can be calculated by the time that the diffracted wave takes to cover this distance. Moreover, a B-scan image can be built after merging a set of A-scans, usually in steps of 1,0 mm, rebuilding a cross sectional image after the displacement of the pair of transducers along the weld.

Advantages, limitations and results: ToFD associates the capability to detect both planar and volumetric discontinuities. It is extremely sensitive for both non-planar and planar discontinuities. *Table 1* illustrates some of the results achieved in tests performed in welds with different discontinuities, to compare the capability of detection among three NDE techniques. The results presented were obtained in a weld plate 10 mm thick.

The comparison of the results can be summarised as follows:

- The first lack of fusion discontinuity was not on detected with RT but detected with both UT and ToFD.
- The second lack of fusion discontinuity was detected with RT, UT, and ToFD.
- The longitudinal crack discontinuity was detected as having a length of 65 mm with RT, 120 mm with UT and 124 mm with ToFD.
- The porosity discontinuity was detected with RT and ToFD but insufficiently detected with UT.

From these results it is possible to conclude that the ToFD technique gives more accurate information. However this characteristic can sometimes be an inconvenience, because it is excessively sensitive and may detect minor discontinuities which could be a waste of evaluation time.

Figure 1 shows another example of a result obtained during the maintenance inspection of the welds of a vessel with 40 mm wall thickness. These indications, not detected in the manufacturing phase with RT, have been detected and recorded with ToFD twenty years later and validated with manual UT. The results obtained were below the evaluation level in accordance with the evaluation criteria (ASME VIII).

For detection of superficial discontinuities, ToFD is insufficient due to the presence of the lateral wave signals and/or the backwall echo, which masks the indications of the superficial discontinuities and therefore, represents a dead zone. To overcome this limitation, ToFD can be accompanied with MP or another UT technique, eg creeping waves.

Also, as an ultrasonic technique, the same parameters that affect the sound propagation in conventional UT can influence ToFD detection capability. Grain size, probe frequency, pulse length, crystal dimension and, specifically for ToFD, the distance between probes, are all factors that can modify the sensitivity and, consequently, the results obtained with this technique.

On the other hand, when diffraction techniques are used, the problems related to reflected signals are avoided due to the fact that it uses the time measurement instead of taking into consideration the amplitude of the signals, which can be affected by differences of coupling, attenuation and the orientation of flaws.

ToFD – with its inherent potential for providing images of the whole inspected volume and the speed at which data can be collected as a result of the single pass technique used – is the ideal tool for discontinuity detection, critical analyses and discontinuity propagation assessment.

		X-Ray			TOFD			UT		
Classification		Start	End	Length	Start	End	Length	Start	End	Length
1	Lack of Fusion	-	-	0	542	578	36	543	567	24
2	Lack of Fusion	670	695	25	670	702	32	670	698	28
3	Longitudinal Crack	940	1005	65	921	1045	124	918	1038	120
4	Porosity	1380	1410	30	1380	1416	36	1380	1400	20

Table 1: NDT comparison.

One of the main advantages of ToFD is that the detection and sizing can be processed in real time with the same data source without the necessity to recalibrate and rescan. This is clearly quite important due to time and cost saving when compared to the UT and RT.

In terms of overall safety, it could be argued and demonstrated that the improved discontinuity reporting accuracy and reliability of ToFD is a very powerful tool in risk assessment and as such, is an important safety tool.

EMAT – Electro magnetic acoustic transducer

The ability to generate an acoustic wave directly within the test material gives to EMAT some advantages when compared to the use of conventional piezoelectric transducers. The physical principle of EMAT, based on the resultant effect of interacting magnetic and electric fields, obviates the need for a couplant layer and all the problems associated with its use.

Due to this significant advantage, EMAT has become the preferred alternative in some applications previously inspected using ultrasonics. One of the most advanced EMAT applications is for boiler-tube residual wall thickness measurement. There are two ways to generate ultrasonic waves using EMAT: via Lorentz forces; or using the magnetostrictive effect. Although Lorentz forces are well known, magnetostriction is the primary generator of sound within a material.

Because the magnetic field necessary to propagate this effect is low and the signal response in amplitude is good, an EMAT generating sound via the magnetostrictive effect is a simpler device to develop. The magnetostrictive EMAT, however, can only produce ultrasonic signals under specific conditions, ie, it must have a magnetic conductive layer on the external surface of the test piece.

This is the case for boiler-tube inspections, where high temperature oxide scale is commonly formed on the external walls. The high temperatures found inside steam boilers, about 500°C, can cause the steam and flue gas constituents to react with steel to form a brittle iron oxide on the inside and outside surfaces of steel boiler tubing [1].

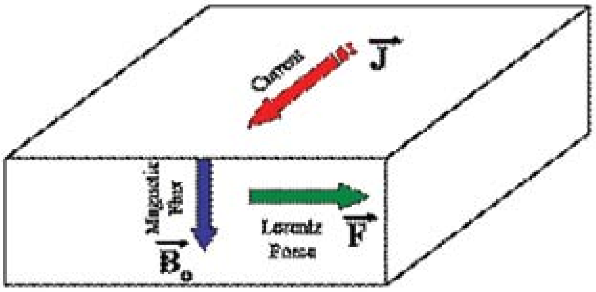


Figure 2:Principle of electromagnetic excitation by Lorentz forces.

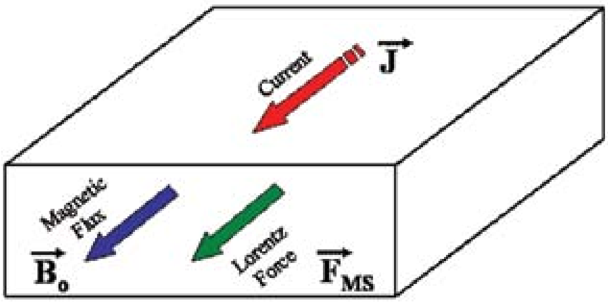


Figure 3: Principle of electromagnetic excitation by magnetostriction.

Basic principles: EMAT generates acoustic waves in electrically conductive materials by the Lorentz force, magnetostrictive effect, or a combination of these two phenomena. Both phenomena act on the atomic lattice of the component so the acoustic wave is generated directly in the component rather than in the transducer, as is the case for conventional ultrasonics using piezoelectric transducers.

The Lorentz force is an interaction between an electric current (J), which is induced by an eddy-current coil, and magnetic flux (B_0). The direction and magnitude of the force F_L is given by the vector product $F_L = J \times B_0$. The Lorentz force, electric current, and magnetic field are therefore at 90° to each other *(Figure 2)*.

Nearly all ferromagnetic materials show a mechanical deformation if they are subjected to a magnetic field. This phenomenon is called magnetostriction. In simple terms, it is the magnetic equivalent of the piezoelectric effect. The deformation is generally parallel to the applied field. If an eddy-current coil is placed at the surface of a ferromagnetic material (eg, carbon steel) dynamic fields are induced which create a dynamic magnetostrictive force (F_{ms}). These forces are generally parallel to the applied magnetic flux B_0 *(Figure 3)*.

To achieve an adequate ultrasonic beam configuration, it is necessary to use large apertures, (ie, large eddy-current coils). Two concepts for the coils exist – one large meander or pancake-shaped coil and an array of small coil segments.

Advantages, limitations and results: Most of the failures in power-generation boiler tubes are caused by rupture of the tubes. Such failure leads to emergency shutdown of the entire unit.

As the boiler ages, general corrosion, pitting and hydrogen damage attack hundreds of steel tubes. The tube walls become thinner or damaged by cracks and eventually, the

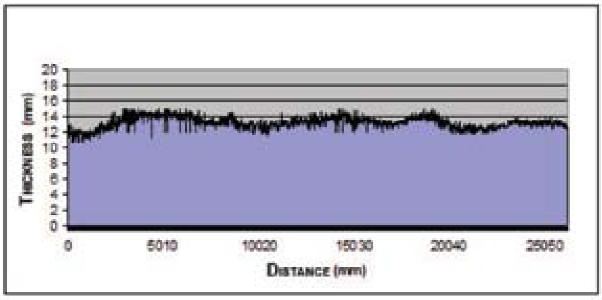


Figure 4: Thickness profile of a boiler tube determined by EMAT inspection.

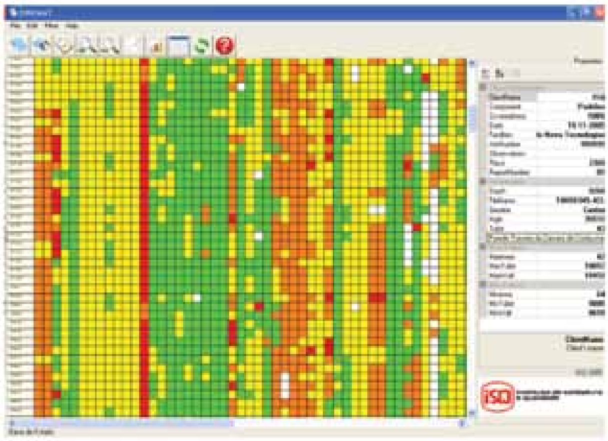


Figure 5: Thickness mapping from a water wall provided by ISQ software after EMAT inspection.

tubes will not be able to withstand the line pressure. Weak tubes must be replaced or repaired long before a burst. For that reason the wall thickness is measured at every shutdown by ultrasonic techniques and/or other damage detection techniques.

At present, ultrasonic inspection involves grinding or sandblasting away the external corrosion layer to expose the bare metal and then applying the acoustic couplant and piezo-electric transducer. This is an expensive and time-consuming process and presents considerable problems, since a typical boiler contains several thousand metres of tubes and only a sample number of measurements can be made.

The EMAT technique shows promise as an inspection technique that can accurately measure the tube wall thickness using shear horizontal (SH) waves and to screen the tube for other damage using guided waves with minimal cleaning and without couplant. By significantly reducing cleaning, the inspection job can be completed much faster, saving the utility a significant amount of time and cost. In addition, there is no need for liquid couplant, further simplifying the test and allowing it to be applied at a much higher temperature. EMAT is capable of generating a variety of ultrasonic wave modes. Typically, EMAT is used to generate SH and Lamb (plate-guided) waves.

A specific UT instrument, able to excite an EMAT and equipped with a portable handheld scanner/encoder, is able to provide a B-scan output that represents the thickness profile of the tube. This EMAT can be used for point-by-point manual measurements and semi-automated B-scan continuous data collection.

The EMAT for the handheld instrument is capable of generating SH waves through any scale with magnetostrictive properties – typical of that produced on the surface of oxidised boiler tubes by exposure at high temperatures. The direct readings are the same as those that would be measured by conventional contact UT but obtained without the use of couplant and on tubes containing scale – generally impossible when using conventional UT.

The B-scan capabilities of the instrument display output data in a format that is easy to use and understand. The technology can be used to produce line scans that show tube wall thickness at selected intervals along the length of the tube. *Figure 4* presents the output of an inspection carried out in a 25-metre long horizontal boiler tube from a refinery. Also, if you have to inspect boilers with vertical tubes, such as water walls, it is useful to be able to present all data acquired in a single map view of the entire wall inspected. *Figure 5* presents a thickness mapping of water wall tubes from a power plant. From this image it is easy to identify the critical thickness points from the colour gradient.

Guided wave inspection

Corrosion in pipe work is a major problem, particularly in the oil, gas, chemical and petrochemical industries. Since a significant proportion of industrial pipelines are insulated, this means that even external corrosion cannot readily be detected without the removal of the insulation, which in most cases is prohibitively expensive. There is therefore an urgent need for the development of a quick, reliable method for the detection of corrosion under insulation (CUI).

The problem is even more severe in cases such as road crossings where the pipe is underground, often in a sleeve. Excavation of the pipe for visual or conventional ultrasonic inspection can cost upwards of €50-thousand, so a technique to address this problem would be particularly beneficial.

Current conventional methods for inspecting the above engineering assets have been in use for approximately 50 years. These have proved inefficient in many applications. The lack of inspection technology has led to major disasters and loss of life when large oil and gas pipelines have failed.

Basic principles: The use of guided waves in NDE has been discussed for over 40 years. Guided waves can be used in three regimes, each of which has been extensively researched: short range (less than 1,0 m), medium range (up to about 5,0 m) and long range (up to around 100 m).

The short range methods include high frequency surface wave scanning, leaky Lamb wave inspection of composite materials and acoustic microscopy in which a leaky surface wave is generated by a lens. Medium range testing typically uses frequencies in the 250 kHz-1,0 MHz range and has been applied to plate, tube and pipe testing, weld inspection, aircraft lap joints, and even to ice detection on aircraft. Long range testing generally requires the use of frequencies below 100 kHz. The use of cylindrical guided waves propagating along the pipe wall is potentially a very attractive solution since they can propagate a long distance under insulation and may be excited and received using transducers positioned where a small section of insulation has been removed.

In order to optimise the technology performance, Guided waves of different types should be available to propagate in any bounded medium. The most attractive modes are those which have a mode shape which has uniform stress over the whole cross section of the pipe. This means that there will be equal sensitivity to cross section loss at any location through the wall thickness or around the circumference.

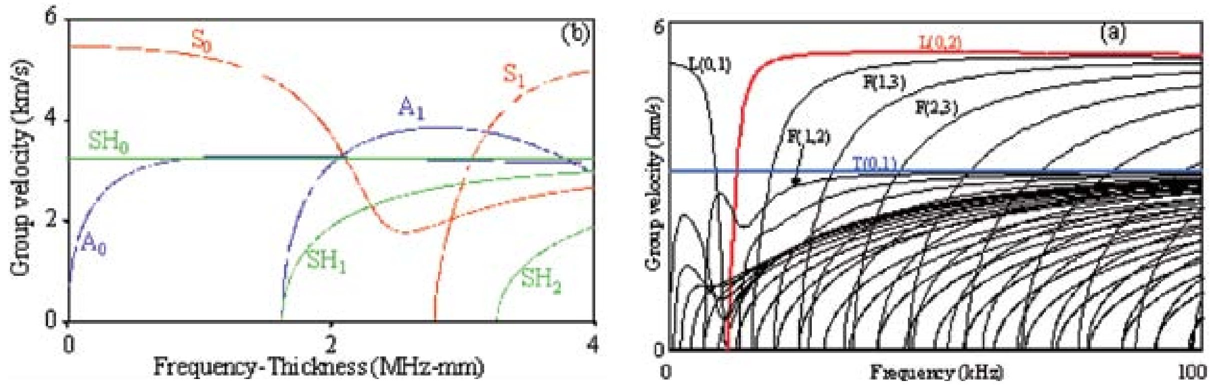


Figure 6: Dispersion curves for (a) six-inch, schedule 40 steel pipe; (b) steel plate [7].

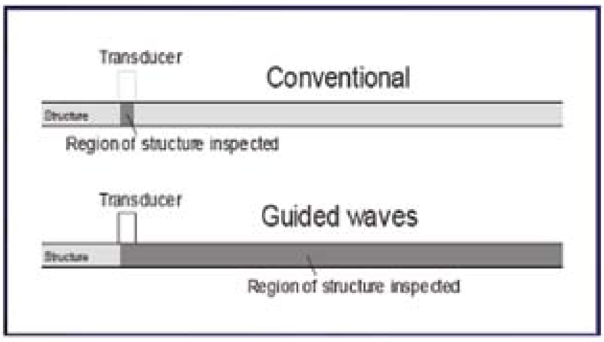


Figure 7: Comparison of the volume of material covered with a conventional single transducer inspection and a guided wave inspection (by GUL Lda).

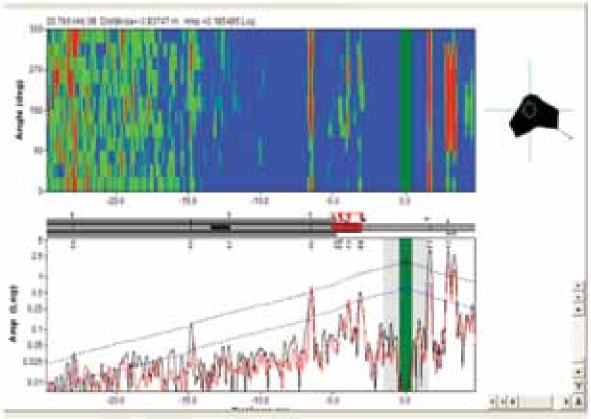


Figure 8: Result obtained from a road crossing pipe inspection, which indicates serious corrosion at the entrance of the wall under the insulation wrapping.

Modes with a simple shape are also easier to excite in a pure form, which is important in controlling coherent noise. The two modes which meet these criteria are the L(0,2) and T(0,1) modes shown in *Figure 6a*. These are essentially extensional and torsional modes respectively. Both modes have the additional advantage of being non-dispersive over a wide frequency band.

The main difficulty with medium and long range guided wave inspection is that it is very easy to obtain signals like that shown in *Figure 6a*. This shows the pulse-echo signal produced on a length of plain pipe by a group of transducers covering a quarter of the pipe circumference and connected in parallel so that they effectively act as a single transducer. Ideally the signal should contain two distinct echoes from the two ends of the pipe rather than the very complicated trace seen in the *figure [7,8]*.

The complication arises from the excitation of multiple modes which travel at different velocities in both directions, and these velocities being a function of frequency (ie, the modes are dispersive). *Figure 6a* shows the dispersion curves for a six inch diameter, schedule 40 steel pipe [7,8].

There are about 50 modes present at frequencies below 100 kHz and many of them are strongly dispersive. *Figure 6b* shows the corresponding diagram for a plate. Here the group velocity is plotted as a function of the product of the frequency and the thickness. Below about 1,6 MHz mm only three modes are present (a_0, s_0 and SH_0). Therefore in a 10 mm thick plate there are only three modes present below 160 kHz. Mode control is therefore easier in a plate than in a pipe but other problems are more difficult, as discussed later [7,8].

The key to controlling coherent noise is therefore to excite and receive a single mode in one direction. The choice of mode will be influenced by the ease of exciting it while minimising the excitation of other modes, and by its sensitivity to the defect type(s) of interest. In addition to controlling coherent noise, it is also necessary to control dispersion. If the chosen mode is dispersive, the different frequency components in the signal travel at different velocities, so the signal duration increases, compromising the spatial resolution – the ability to distinguish echoes from closely spaced reflectors. Strategies to overcome dispersion problems – by applying narrow band excitation centred on a region where the mode of interest is non-dispersive – are often sufficient, though dispersion compensation can also be valuable [7,8].

Advantages, limitations and results: The main attraction of long range guided wave inspection is that it enables a large area of structure to be tested from a single transducer position, so avoiding the time-consuming scanning required by conventional ultrasonic or eddy current methods. The technique becomes even more attractive if part of the structure to be tested is inaccessible, for example a pipe passing under a road. The test is usually done in pulse-echo mode, the transducer transmitting the guided wave along the structure, and returning echoes indicating the presence of defects or other structural features.

Recent developments have used guided ultrasonic waves with ranges of 10s of metres or more (long-range inspection). Such waves can solve the otherwise intractable problems of

Figure 9: Corrosion patches revealed after removing the insulation at the location indicated by guided waves inspection.

inspecting engineering assets. The guided wave technique has the advantage of full volume coverage and the ability to test long lengths of structure from a single point. It can also be used to inspect inaccessible regions of a structure from an accessible location, so potentially defective areas are located accurately in terms of distance from the transducer ring.

Figure 7 illustrates the guided wave technology as compared to conventional techniques while *Figure 8* and *Figure 9* present results from a road crossing inspection.

Phased array inspection (PA)

Ultrasonic phased arrays have emerged in the past few years as a very powerful form of applied ultrasonic testing in NDE. Computerisation has played a key role in enabling the technology to develop and has provided a software platform for innovative data gathering and analysis tools to be developed.

For a long time phased array technology was almost the exclusive domain of the medical world as the use of phased arrays in the NDE industry was considered too complex and the cost of producing phased array equipment, prohibitive. Over the past decade the benefits of using phased arrays as a viable alternative to certain other NDE technologies has been realised.

For manufacturers of computerised ToFD and pulse-echo equipment, phased array was a natural progression for integration with existing ultrasonic technologies or indeed for stand-alone systems.

PA technology requires the use of a probe formed by a mosaic of many transducer elements, capable of being excited individually and independently without acoustically or electrically interfering with adjacent elements.

The performance of each element must be as exact as possible to assure a homogeneous formation of the beam. Due to its composition, and after the first pulse, PA probes present a smaller dead zone.

Active elements in the first PA probes were manufactured of piezoelectric material, but technological development now allows probes to be manufactured from piezocomposite material, formed by ceramic elements arranged in an electrically inert polymeric matrix. This structure gives PA probes the necessary acoustic performance required for real inspections [10].

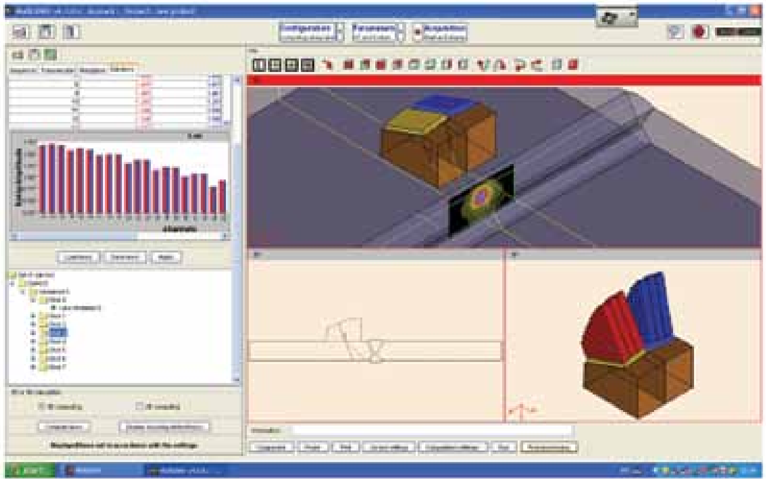


Figure 11: Numerical simulation of a stainless steel weld inspection conducted using a tailor-made phased array matrix probe.

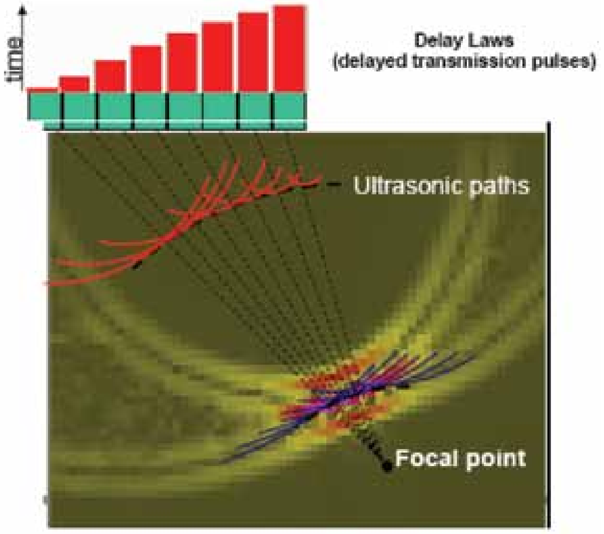


Figure 10: Generation process of a wave front in a linear phased array probe [by M2M].

Basic principles: The physical concepts associated with the PA technique are the same as those of conventional UT. In practice, many of the basic concepts are learned in UT level-1 courses, such as length of the near field, calculation of the diameter of the beam, divergence of the beam. All these concepts can also be used in the evaluation of a beam generated by PA equipment.

The function of PA equipment includes the construction and the electronic management necessary to transmit and receive an ultrasonic beam. There is no real difference between a compression wave generated by a single crystal probe and a wave produced by a PA probe. Both have similar properties – frequency, dimensions, etc. The generation process of a wave front is governed by the basic Huygens concept in both cases [9]. The sound beam is generated electronically by means of specific software that excites the element's transducers in the probe, thus originating a wave front as illustrated in *Figure 10*.

The electronic construction of the wave front is governed by the following theoretical principles: the delay law, the focal law and Huygens' principle. The delay law describes the difference in time that each transducer is excited to produce a pulse, or the delays or phases applied to each transducer element when a signal is emitted. The focal law is associated with the characteristics of the sound beam itself – its angle and its focal point – which are both dependent on the delays and the gain applied to each transducer element. The focal law is defined as the association of the principles of the delay law and the signal amplitude law.

Huygens' theory, as applied to PA, means that a wave front can be constructed by the addition of single waves emitted from an infinite number of sources, waves that differ in space and/or phase. It is thus possible to control the delay of each pulse so that, when added, a wave front of the required sound beam is generated. During the emission of a signal, not all elements need be activated, thus the size and the location of the beam aperture can be accurately controlled.

Advantages, limitations and results: When compared to conventional ultrasonic systems, PA systems allow wider beam coverage, better signal to noise ratios, improved inspection flexibility and an overall improvement in the detectability of discontinuities such as porosities, lack of fusion or cracks.

By using electronic tools such as electronic scanning, electronic focussing and electronic steering, the technique is able to provide a more complete inspection. The combination of dynamic beam control and dynamic depth focusing makes for better and faster scanning of the zone possible. Sophisticated software allows more consistent and reliable set up and the results presented are usually more detailed and easier to interpret than conventional UT [9].

The versatility of the PA technique allows the inspection of complex geometries, possibly the major advantage of applying this type of equipment. Another important application is the inspection of anisotropic material that usually requires a very complex and not fully reliable approach using conventional UT. *Figure 11* presents a simulation of stainless steel material by using a tailor-made Phased Array probe to optimise the inspection.

Conclusion

NDE advanced tools, based on ultrasonic principles such as ToFD, EMAT, guided wave and phased array, have been developed and implemented recently for on-site inspection.

As is the case with any NDE technique, each one has inherent advantages and limitations but it is undoubtedly evident that new solutions are being realised because of these techniques.

This is crucial to the development of the world-wide industry particularly in the light of safer risk analysis and more accurate remaining life assessment requirements.

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