BASIC PRINCIPLES AND UTILIZATION POSSIBILITIES OF ULTRASONIC PHASED ARRAY IN MATERIAL NONDESTRUCTIVE EVALUATION

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Summary. The paper deals with the basic principles of operation and with the utilization possibilities of phased array (PA) in materials nondestructive testing (NDT). The first part deals with description of PA arrangement modes, which enable to generate, focus and steer the ultrasonic beem. The second part deals with the description of electromagnetic acoustic transducer PA operation. The last part deals with the description of the utilization of PA in nondestructive testing of conductive materials and the advantages of PA utilization in inhomogenous materials NDT.

1. INTRODUCTION

Nondestructive testing techniques based on ultrasonic phased array technology are more and more applied in various industrial context, as they provide improved adaptibility to different inspection configurations. Among those configurations, two specific items have to be assessed that usually limit the inspection performances – irregular geometrical profile and complex materials. As a conventional probe is moved over an irregular profile (whether the probe is used at contact or immersion), the radiated beam may be drastically modified in terms of sensitivity and orientation, so that the detection and characterisation of actual defects may not be ensured. Ultrasonic inspection of complex – in terms of material and geometry – structures has to overcame major limitation: unknown actual direction and focusing pattern of the transmitted beam, which leads to degraded performances for detection and identification of defects , complex interpretation of results due to spurious echoes or multiple modes, low signal-to-noise ratio due to sensitivity loss, etc. The use of multiple transducers and/or settings allow to perform different techniques which may give the better results. Obviously, phased array techniques provide an efficient alternative way to improve the adaptibility and flexibility of the inspection methods, compared to standard probes, as they may be used to master the ultrasonic beam thanks to delay or amplitude laws, for instance for any scanning position of the array probe moved over a varying profile. Phase array probes may also be used to transmit/receive waves through complex layered specimen, thus to select and perform the optimum inspection mode.

2. PRINCIPLES OF OPERATION AND FEATURES OF PHASED ARRAY

A conventional ultrasonic (UT) probe consist of a piesoelectric element, while that for phase array UT probe has multiple piezoelectric elements, very close together (on the order of a wavelength of sound). Large conventional ultrasonic probes give good flat coverage but have a small beam angle. Small elements have a much larger beam divergence angle. It is this large angle that makes possible the most useful features of the phased array technique - beam steering and dynamic focusing. In its simplest form, an array is a single large transducer (piezoelectric material) cut into very small segments or elements. It takes less energy to excite the smaller mass of these tiny elements. As a result, they transfer and receive energy with much greater efficiency.

A linear array can steer the beam by pulsing the individual elements of the array at different times. The individual "wavelets" combine to form a straight or oblique beam. By controlling the phase during reception of each element you reverse the process and produce a electronically stearable and focusable beam. The phase of the pulses driving each element can be controlled. This is equivalent to controlling the time delay between each pulse and all the others. The sound waves combine (add) according to these delays or phases and can be focused and steered electronically. This can be done very fast so real time images can be formed that can be in focus everywhere. Because the linear array is only phased in one direction the electronic focus is a line focus, very much like a cylindrical transducer with an electronically controlled focus and direction.

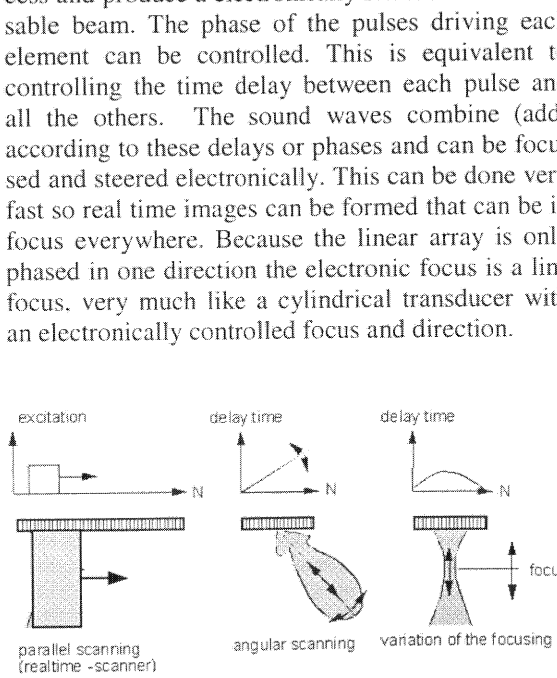

Fig.1. Sound beam steering by phased array probes

The division of a radiating surface in single elements which can be exited with different delay times and sensitivities allows an electronic soundfield steering offering 3 basic possibiliteies of beam region character, Fig.1.

One can move a beam along the line of a linear array which is the parallel scan of the medical diagnostic. More important for NDT is the sector scanning using shear- or longitudinal waves, depending on the angle of incidence and possibly also on wedge angles as demonstrated, Fig. 2.
A more or less curved distribution of the delaytimes produces a focusing which can also be used to compensate the influence of curved coupling surfaces.

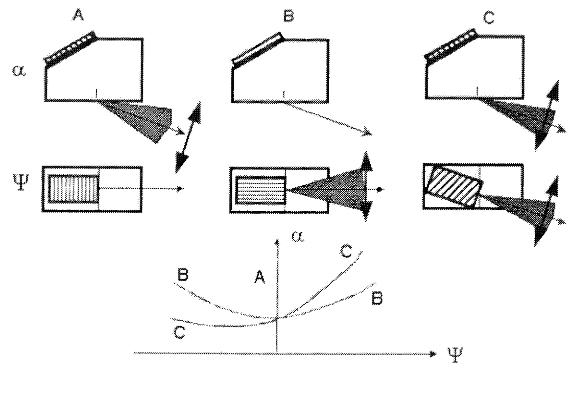

Fig.2. The basic possibilities of wedge equipped probes with a linear phased array

The basic possibilities of beam wobbulation, Fig.2 of wedge equipped probes with linear phased array are shown: variation of the incidence (A), the skewing (B) and angle (C). The angle can be changed only within the plane of incidence. One may produce mainly skewing angle variations within the plane perpendicular to the plane of incidence By a combining probe type with a rotated linear phased array system one produces skewing- and incidence angle variations.

Typically, element sizes of phased array range from 0.5 - 2.54 mm although arrays can have custom element sizes and can be arranged in custom configurations with the particular geometry developed to meet an ultrasonic application need. Linear, annular (circular elements divided into doughnut-shaped elements) and matrix arrays are In basic configurations.

Linear array probes, Fig.3 -1

These probes are made up of a set of elements juxtaposed and aligned along an axis. They enable a beam to be moved, focused, and deflected along a plane.

Annular array probes Fig.3-2

Annular array probes are made up of a set of concentric rings. They allow the beam to be focused to different depths along the axis of the transducer. The surface of the rings is in most cases constant, which implies a different width for each ring.

Matrix array probes Fig.3-3a, 3b

These probes have an active area divided in two dimensions in different elements. This division can, for example, be in the form of a checkerboard, or sectored rings. These probes allow to be driven by combining electronic focusing and deflection.in space.

These probes are made up of a set of elements arranged in a circle. These elements can be directed either towards the interior, or towards the exterior, or along the axis of symmetry of the circle. In the latter case, a mirror is generally used to give the beam the required angle of incidence

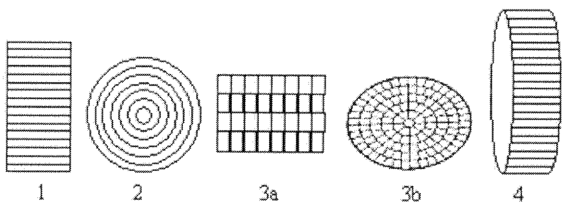

Fig.3 Examples of geometries of phased array transducers elements

The advantages of using phased array technology are the technical and economic benefits gained:

traditional mechanical scanning is replaced by the much faster electronic scanning

electronic focusing allows the use of a single probe for working at different depths

electronic deflection allows the angles of incidence to be varied with only one probe.

Costs are thus significantly reduced because of the inspection and adjustment time saved.

In addition, phased array technology has made some applications possible that could not be resolved by traditional solutions, for example, when beam deflection is necessary without enough space to use a wedge (rotor steeple and blade root inspection) or when scanning is necessary without enough space

3. EMAT AND PHASED ARRAY

Electromagnetic–Acoustic Transducer (EMAT) technology is a Non Destructive Ultrasonic Testing method that differs from piezoelectric ultrasonics in the way the sound is generated. In traditional ultrasonics a piezoelectric crystal is used to transduce electrical energy into mechanical energy. The vibration makes its way into the test piece via the couplant.

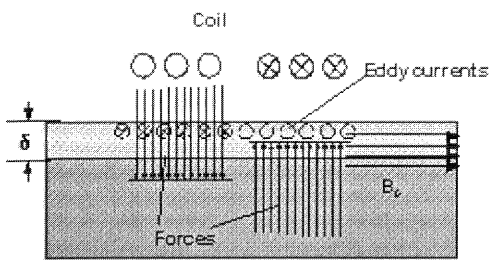

Fig.4 Principle of electromagnetic acoustic generation

An EMAT consists of a magnet and a coil of wire and relies on electro-magnetic acoustic interaction for elastic wave generation. Using Lorentz forces and magnetostriction, the EMAT and the metal test surface interact and generate an acoustic wave within the material. The material being inspected is its own transducer, eliminating the need for liquid couplant.

The electromagnetic acoustic excitation of ultrasound is based upon two physical mechanisms: the Lorentz forces and the magnetostriction in ferromagnetic materials.The theory we expose here describes the acoustic electromagnetic phenomenon only using Lorentz forces. A coil, placed near the surface, transmits an r.f electromagnetic signal (Fig.4). The response of the metal takes place in the classic skin depth δ , where electrical field **E** and their associated eddy current density **J** are induced.

When static magnetic field is applied $\mathbf{B}_0$, the balance is disturbed, giving birth to a force that acts on electron, it is the Lorentz force given by the following relation

$$\mathbf{F} = \frac{\mathbf{J} \times \mathbf{B}_0}{n_0}, \qquad (1)$$

where n_0 is the electron density. For $\mathbf{B}_0$ oriented according Ox the Lorentz force is longitudinal, resulting in a variation of the electron charge density along Oz. An internal electrical field **E** oriented following Oz has to exist to maintain charge neutrality. Its ions come in an compressional oscillations of amplitude ξ_z. For $\mathbf{B}_0$ oriented according to Oz, the currents **J** are to Oy direction and the Lorentz force act in the Ox direction (this orientation is shown in Fig.4) The Lorentz forces act to produce a shearing force along Ox arise shear oscillations of amplitude ξ_x. Thus for these two polarisations , the acoustic wave equation is

$$\frac{\partial^2 \xi}{\partial t^2} - s^2 \frac{\partial^2 \xi}{\partial z^2} = \frac{|\mathbf{J} \times \mathbf{B}_0|}{d}, \qquad (2)$$

where d is the density of the metal and s the speed of ultrasonic wave. In non- ferromagnetic materials the Lorentz force is the one contribution to the generation of sound. In a ferromagnetic material, additional forces are produced by magnetostrictive stresses. Ultrasonic wave is no more a linear function of the applied magnetic field. According to these principles an EMAT then consists of a means for producing a static bias field, i.e., a permanent magnet or electromagnet, plus a coil of wires carrying a dynamic drive current.

EMAT provides all of the capabilities of ultrasonic testing with some distinct advantages. These unique advantages make it especially well suited for automated applications in industrial environments. An EMAT probe becomes a simple end-of-arm tool that combined with the proper electronics and software can be integrated into a production line to provide reliable inspection without human intervention.

EMAT technology, combined with phased array techniques (principles are shown in chapter 2) uses horizontally polarized shear waves to improve the inspectability of stainless steel welds, dissimilar metal welds, buttered welds, cladding, etc. These, and other components can now be completely inspected regardless of access considerations due to the virtual transparency of the material to horizontally polarized shear waves. The inspection for hard to detect flaws such as intergranular corrosion cracking in stainless steel piping welds or cast stainless steel welds is made possible with unmatched accuracy and ease.

Although EMAT can generate SH wave, which is suitable for detection of flaws in the austenitic welds, conventional EMAT has such disadvantages as shorter pulse length and poor time resolution. The phased array method enables pulse length to shorten and makes the scanning condition (incident angle) optimized by using the variable angular function. The operation of phased array is always constrained by the size of the array and the spacing of the elements to a limited range of wavelenght.

4. EXAMPLES OF ULTRASONIC PHASED ARRAY APPLICATIONS

A certain number of industries requiring advanced means of Non-Destructive Testing, such as the nuclear, aeronautic or in-line testing industries, constantly seek improvements in the performance of their monitoring systems.

Inspection of blade roots and rotor steeples

This inspection, carried out using various miniaturized phased array probes
The use of phased array technology has enabled the use of beam-deflecting wedges to be avoided, and thus inspections to be carried out from restricted spaces inaccessible with other techniques. In addition, the probes' electroacoustic performances have enabled the depth of detection and the accuracy of sizing to be increased

Inspection of tubes

Several phased array techniques can be used for inspecting tubes. In-line testing of tubes is generally done from the outside with encircling probes.

Inspection of heat exchanger tubes is generally done from the inside for reasons of accessibility. Phased array technology enabled the required testing speed to be achieved. In addition, the active area, made up of piezoelectric elements or coils, is focused by shaping to obtain the required beam characteristics. This inspection can also be carried out from the inside and from the outside by using a flat circular array associated with a mirror.

Inspection of titanium billets

Titanium billets are traditionally inspected with sets of single-element probes, where each probe is dedicated to the inspection of a specific zone (depth range), for a specific diameter of billet. Although efficient in detecting defects, this solution has the major disadvantage of requiring many probes, and several shots to inspect a single billet. An alternative consists in using a matrix array. The cutting of the elements, such as shown in Fig.3 and the electronic focusing and deflection enable the probes to be adapted to different diameters of billets and to different working depths. It is also possible to use the time reversal mirror technique.

High temperature nuclear vessel inspection

The design of phase array probe has to combine the large aperture of the transducer and the thermal constraints. Mechanical properties of piezocomposite material of phased array allowed to withstand the temperature variation, while keeping the shape and performances of the active area.

5. CONCLUSION

The growing needs of NDT.ultrasounds to reduce untested areas, improve the speed of inspection and increase detection and sizing performance, have resulted in recent years in the development of advanced sensor technologies, such as phased array sensors These latest generations of sensors use the key Piezocomposite 1-3 technology to achieve their acoustic component.The electroacoustic performance of these piezoelectric materials, combined with their mechanical properties, have enabled improvements to be made in many inspections and new inspections to be made that were not possible using sensors with a monolithic piezoelectric element. The main advantages of EMAT phase array are electronic control of the sound beam angle and shape generation of horizontally polarized shear wave mode, generation of vertically polarized shear wave mode (standard shear wave) and Rayleigh wave mode, no acoustic coupling medium required.

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