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R&D n° : 47-3-0027-4

April, 92

**ON THE USE OF THE ULTRASONIC BEAM FOCUSING TECHNIQUES**

**11th INTERNATIONAL CONFERENCE ON NDE  
IN THE NUCLEAR AND PRESSURE VESSEL INDUSTRIES**

**Albuquerque (NM), 30 April - 2 May 1992**

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# On the Use of the Ultrasonic Beam Focusing Techniques

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## ABSTRACT

The beam focusing technique has gained a wide recognition for the volumetric inspection of nuclear reactor pressure vessel welds. However, the specific advantages of beam focusing, in terms of examination sensitivity and resolution, may be utilised in many other NDE applications, in the nuclear and in the conventional industry.

Several examples are taken from various fields to show how customising of the beam shape can solve industrial problems, in a much more effective way than conventional pulse generation methods. The enhanced capability of focusing transducers for high scattering materials is illustrated and analysed. In addition, the possible combination of beam focusing with other advanced techniques, such as pitch-catch examination, flaw tip diffraction and digital signal processing is emphasized.

On the other hand, the implementation of focused beam probes requires several precautions to be taken, from the design of the examination to the analysis of the scanning data. The paper deals with various peculiarities in relation with the characterisation, the calibration and the qualification of the search units.

THE CAPABILITY OF CONVENTIONAL ultrasonic transducers and associated inspection procedures often turns out to be inadequate where high examination sensitivity or accurate flaw sizing are required. This holds particularly in the case of high scattering materials, such as austenitic stainless steels.

Most shortcomings of standard search units are induced by the natural divergence of the acoustic beam they generate. The following shows that ultrasonic beam focusing offers a very convenient alternative.

## PRINCIPLES OF ULTRASONIC BEAM FOCUSING

Ultrasonic beam focusing designates any technique that consists in skewing the acoustic rays emitted by a piezoelectric element, in such a way that the sound field energy concentrates in a limited volume of the test material, usually referred to as the focal zone. Fig.1 shows the characteristic beam shape and acoustic pressure distribution of a focusing probe. The focal length  $F$  indicates the peak position of the sound pressure distribution. Focusing beyond the nearfield of the corresponding planar transducer cannot be achieved. The following expressions give a fair approximation of the focal diameter  $d$  and of the focal zone length  $L$  :

$$d = \lambda \frac{F}{D} \quad (1)$$

$$L = 4 \cdot \lambda \cdot \left(\frac{F}{D}\right)^2 \quad (2)$$

where  $\lambda$  is the acoustic wavelength in the insonified medium and  $D$  is the piezoelectric element diameter.

Due to the concentration of acoustic energy around the focus, the examination sensitivity is considerably increased, yielding a higher detection probability for small or low reflectivity flaws. In addition, the fact that a smaller volume of material is insonified by the beam, leads to an enhancement of the signal-to-noise ratio (SNR).

Very narrow beams can be obtained, yielding an excellent lateral resolution. This allows for the discrimination of adjacent flaws, and for accurate contouring and sizing of flaws. On the other hand, the finite extent of the depth range generally requires two or more transducers to examine the full thickness.

As the emitting surface of a focused beam probe does

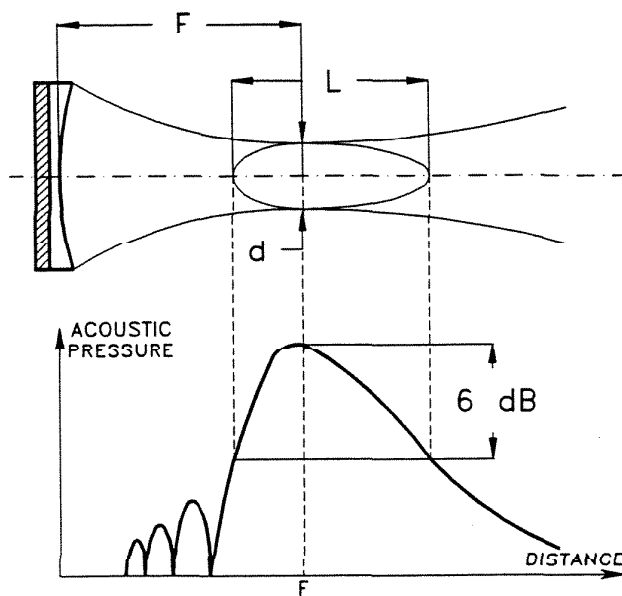


Fig.1 : Focused beam characteristics

not coincide with the inspection surface, a coupling medium must be provided. Consequently, focusing transducers are particularly suited for immersion type inspections. When the components to be tested cannot be immersed, appropriate coupling can be provided by local immersion devices or, in the case of small transducers, by plexiglass wedges.

#### PROBE DESIGN CONSIDERATIONS

The introduction of refractive and reflective acoustic elements along the sound path offers a much more versatile tool to the focused probe designer, than the use of curved piezo-electric elements. In most industrial applications, an acoustic lens with appropriate material characteristics (acoustic impedance, attenuation) is fixed onto a planar piezo-electric element. Though less flexible, and therefore more expensive, permanent fixing is preferred to removable lenses, which affect signal repeatability and waste sound energy in multiple interface reflections. The materials most commonly used for the fabrication of acoustic lenses are epoxy and acrylic resins and polyesters.

**SPHERICAL AND TOROIDAL LENSES.** The principles of refraction and reflection of elastic waves are to a large extent analogous to those of light waves. Therefore, basic considerations of geometrical optics can be

transposed to sound wave focusing, to yield mathematical relationships between the radius of curvature of the acoustic lens and the focal length of the probe (1,2).

For the inspection of planar components in normal incidence, spherical lenses provide appropriate focusing of the sound beam. In case of angle beam examination, or if the interface between the coupling medium and the test specimen is curved, the refracting conditions have to be analysed independently in the incident and the perpendicular plane, as shown schematically in fig.2. To achieve proper focusing conditions, a bi-spherical or toroidal lens is commonly used, with a different radius of curvature in either plane.

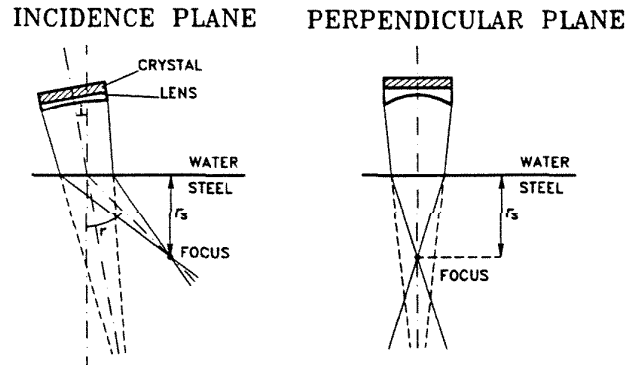


Fig.2 : Design principle of bi-spherical lens

In the design practice, calculation programs are used to generate the optimal shape of the beam, taking into account the focal length, the refracted angle and the curvature of the inspection surface. To validate design, the compatibility of the values predicted for the beam parameters in both planes are verified, and corroborated by acoustic intensity measurements.

As a general rule, focal depth is imposed by the application, while parameters such as wave mode, frequency and refracted angle, are dictated by considerations similar to those used with conventional search units. Setting those parameters still leaves a continuous range of possible beam diameters, from sharp focusing to unfocused (and even defocused) beams.

Most often, narrow beams will be preferred for flaw characterization applications, whereas large detection scans will be more appropriately performed with moderately focused beams. An application of sharp focusing is described in (3) : to perform accurate sizing of flaws near to the far surface of a V-shaped weld, contact transducers were developed, generating shear waves at 45° in steel. A liquid lens in the solid shoe of the probes yields a beam diameter of 1.5 mm at 30 mm in depth.

**OPTIMIZED LENSES.** Conventional spherical lens

design fails to provide appropriate focusing where high refracted angles or wide apertures induce large aberrations. Calculation can determine the surface that generates ultrasonic rays converging, in phase, to the focal point (fig.3). That equiphase surface or Fermat's surface is a surface of revolution, that can be expressed mathematically as a function of the given configuration. The machining of its exact form is generally a fairly complex matter. The so-called optimized-lens design is based on the calculation of local approximations, yielding an efficient compromise between machining considerations and aberration compensation.

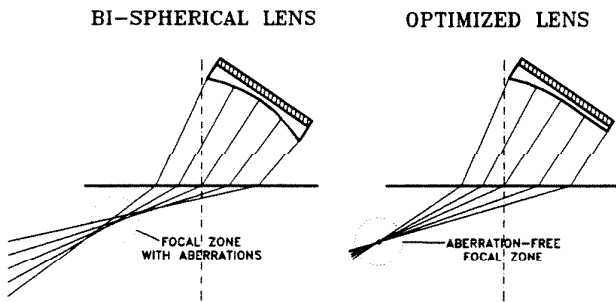


Fig.3 : Spherical versus optimized lens design

Typical applications of the optimized-lens technique can be found in many probes developed for the detection and sizing of shallow defects, such as under-clad cracks.

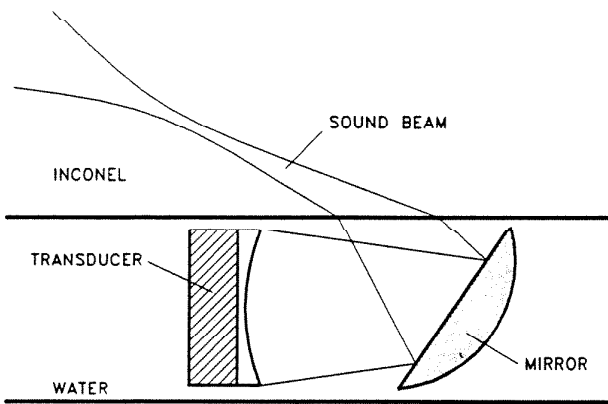


Fig.4 : Application of an acoustic mirror

ACOUSTIC MIRRORS. The use of an acoustic mirror is an appropriate solution to generate focused beams where access limitations require folding of the soundpath in the coupling medium. The design principles are identical to those applied for lenses, except that focusing is achieved through reflection of the ultrasonic rays.

Clearly, the combination of both lenses and mirrors can offer still more design flexibility. Fig.4 shows a schematical representation of a probe developed to inspect inconel set-on nozzle welds from the borehole (4). The sound beam of a 4 MHz transducer is deflected by a convex acoustic mirror and generates compression waves at 45° in the nozzle material. The mirror curvature in the perpendicular plane compensates for the focusing effect induced by the borehole interface. Focal diameters as small as 4 mm were achieved.

BEAM FOCUSING COMBINED WITH OTHER TECHNIQUES

AUSTENITIC STAINLESS STEEL INSPECTION. Basic considerations aiming at the improvement of ultrasonic examination capability of austenitic materials, have been described in several references (5-7). Since ultrasonic beam focusing strictly consists in modifying the geometrical shape of the sound beam, those considerations will remain equally valid while using focused probes.

Eq.1-2 show that the focusing technique allows appropriate shaping of the acoustic beam, taking into account the choice of the wave type and the frequency range imposed by the material structure. However, coarse grain austenitic steels are known to act as a low-pass filter on the ultrasonic signal, reducing considerably the actual working frequency (6). Consequently, correct lens design can be achieved only if the actual frequency of the pulses propagated in the material is known.

Highly damped transducers are recognized to reduce the degree of scattering that occurs during the propagation in coarse-grain materials (6). Simultaneously, heavy backing reduces the sidelobes of

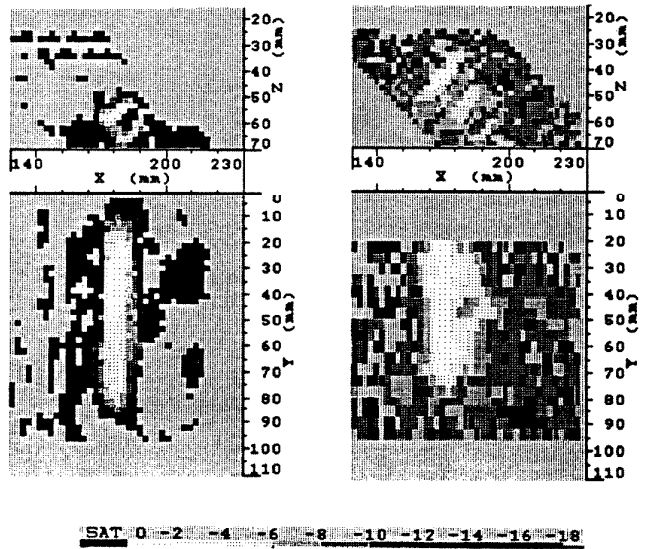


Fig.5 : B-scan (up) and C-scan (down) views of a 4 mm diameter SDH in SCSS ; focused beam probe (left) and TRL probe (right)

focused beams, and improves the depth resolution.

Experiments have shown that focused beams are less distorted by the austenitic macrostructure than conventional divergent beams. Those observations have been corroborated by numeric simulations using ray-tracing models (8), which pointed out that focal characteristics of angle beams of compression waves and horizontally polarised shear waves are not seriously modified by the anisotropic grains.

Fig.5 illustrates the improvement that beam focusing can provide : it compares the results obtained by a TRL search unit and a focused probe, on the same reflector machined in a statically cast stainless steel sample : with the same frequency (0.5 MHz) and refracted angle (45° compression waves), a SNR improvement of about 6 dB is achieved.

**FLAW TIP SIGNALS.** When considering crack-like flaws, the detection of tip echoes allows for accurate sizing. Due to the enhanced signal-to-noise ratio of focused beam probes, those generally low amplitude signals can even be detected in high scattering materials. Fig.6 shows the echoes generated by a 20 mm deep slot spark-eroded in a 200 mm thick statically cast stainless steel sample : the upper tip signal can be clearly distinguished from the corner reflection, using a large 0.5 MHz transducer refracting compression waves at

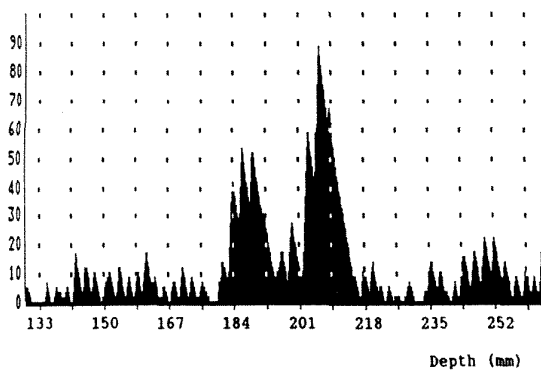


Fig.6 : Tip and corner echo of a spark eroded slot

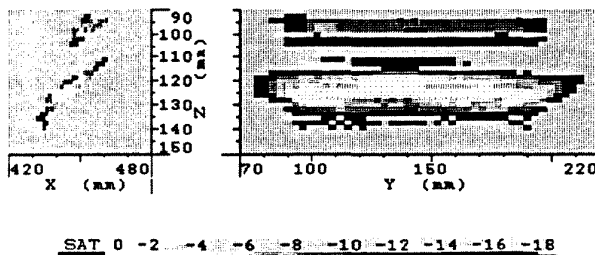


Fig.7 : Diffraction signals of an embedded sharp flaw : B-scan (left) and D-scan (right) views

30° (9). Additional experiments were performed on sharp flaws implanted by diffusion welding. Several test blocks, fabricated for the PISC II parametric studies (10), were made available by the CEC JRC Ispra. Fig.7 shows signals diffracted from the upper and lower edges of an embedded flaw. A transfer of the signal amplitudes to coarse grain austenitic steel, leads to a SNR of about 8 dB.

**PITCH-CATCH TECHNIQUE.** In some cases, a pulse-echo inspection may be unable to discriminate between a surface-breaking crack and a volumetric flaw close to the far surface, whereas the relevance of those reflectors is quite different as to the structural integrity of the component. Fig.8 illustrates how a pitch-catch mode examination can provide additional information about the flaw type. Numerical simulations can quantify the strong dependence of the smallest detectable crack height on the diameter of the insonifying beam, highlighting the superior capability of focused probes.

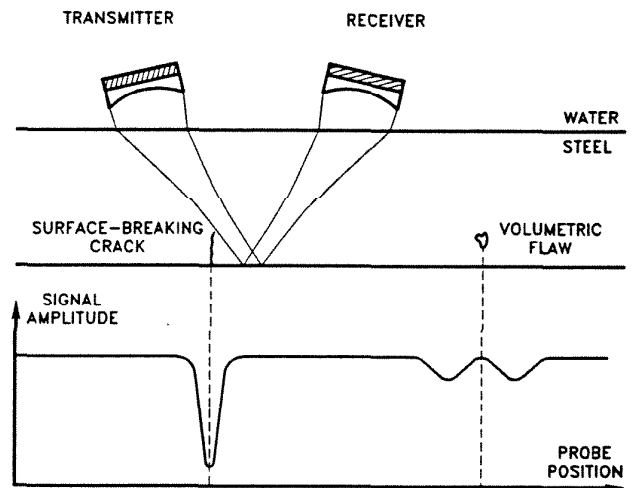


Fig.8 : Principles of the pitch-catch technique

**SIGNAL PROCESSING.** A number of digital signal processing algorithms, working in either the time or the frequency domain, are known to enhance the signal-to-noise ratio. The improvement induced by these techniques, is fully compatible with the intrinsic benefits of beam focusing.

**THE IMPORTANCE OF CHARACTERISATION, CALIBRATION AND QUALIFICATION**

**CHARACTERISATION.** The design flexibility offered by the focusing technique may give rise to rather complex inspection configurations. Precise knowledge of actual

probe parameters, is essential to both the evaluation of the testing capability and the interpretation of the examination data. This is obtained through characterization measurements. To fully benefit from the well-known advantages of automation, in terms of accuracy and reliability, the use of such procedures should become standard practice among probe manufacturers.

The effective refracted angle, the beam exit point and the coupling medium delay can be determined by automated scanning of calibration blocks containing side-drilled holes in the focal zone of the probe. Furthermore, the characterization program must provide information about lateral and depth resolution: the beam diameter can be determined by analysing scans performed on flat-bottomed holes, while time domain analysis of the ultrasonic signal yields the effective pulse length in the material.

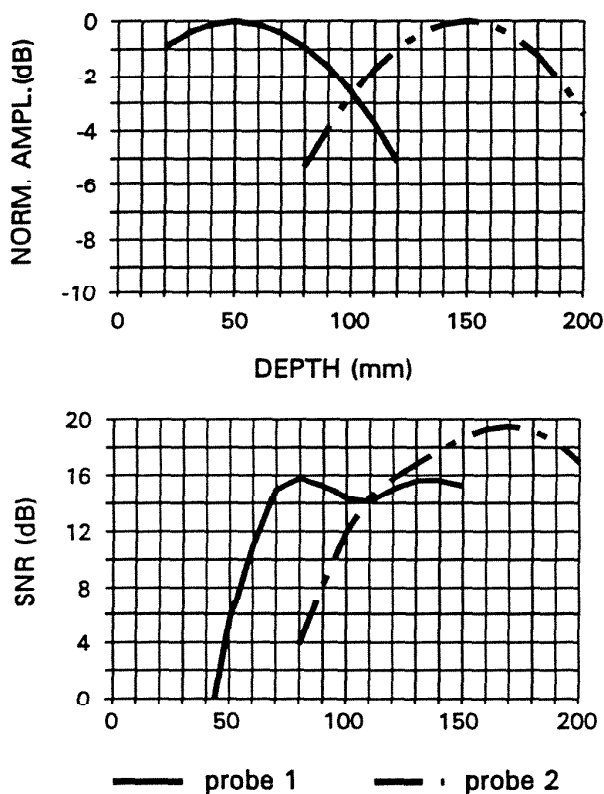


Fig.9 : Sensitivity (up) and SNR (down) curves of probes covering different depth ranges

**CALIBRATION.** Test blocks for the calibration of ultrasonic equipment featuring focusing transducers, must be representative for both the material structure and the geometry (surface curvature) of the real component. The sensitivity and the SNR curves of each probe must be

determined (fig.9) from the amplitudes recorded on reference reflectors at appropriate depths. Correct overlapping of the depth ranges of the different transducers is determined from both sensitivity and SNR curves. When realistically shaped specimens are not available, the actual sensitivity curves must be deduced, through transfer algorithms, from measurements on available geometries.

**QUALIFICATION.** The setup of an automated inspection system, in terms of sampling frequency and scanning step, can strongly influence the recorded echo amplitudes. As narrow focused beams yield steeper echodynamic curves than conventional transducers, smaller scanning steps must be used to maintain the accuracy of amplitude measurement.

The lateral and depth resolution of the global system can be found by combining the beam diameter and the pulse length of the probe (measured during the characterisation program) with the settings of the data acquisition unit. Sensitivity and SNR are known from the calibration exercise, yielding essential information about the detection capability of the technique.

Locating and sizing accuracy should be deduced from performance demonstration tests performed in realistic inspection conditions. In addition, statistical methods can provide useful estimates of the influence of equipment or environment variables affecting the global accuracy.

#### SUMMARY

Principles, design practice and applications of the focusing technique have been reviewed, illustrating its various advantages.

Beam focusing indeed enhances the examination capability, and may be customised to meet a wide variety of user's requirements.

It was emphasized however that, to fully exploit the power of the technique, attention must be paid to the test configuration, and to all parameters affecting the propagation of the pulse waves. With respect to this, probe characterisation and qualification should always be seen as essential parts of the technique implementation.

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