

## **MECHANICAL ENGINEERING**

### **Application of Ultrasonic Phased-array Techniques for Inservice Inspection**

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**Abstract.** This paper gives a brief overview of modern ultrasonic inservice inspection techniques using a phased-array system. Experimental results on the application of the system in the nuclear field are discussed, especially the measurements carried out on geometries which are complicated in relation to the ultrasonic inspection. These are, for instance, the spherical bottom or dome of nuclear pressure vessels or the inner nozzle radius. In order to solve this inspection problem it must be considered also that there is a very reduced accessibility for the ultrasonic probes. Further, the principle of the data acquisition and evaluation is described.

#### **Introduction**

The availability and high operation security of nuclear power plants require sophisticated inservice inspection techniques during their life-time. In the Federal Republic of Germany a periodic inspection must be carried out after every 4 years. Therefore, to guarantee this safety concept in the research laboratories a lot of development was necessary. For safety operation, the knowledge about defects and their position within or at the surface of the material is very important. Therefore, nondestructive testing methods such as ultrasonic methods are used for the detection of defects like cracks, pores or slag inclusions.

The most significant components for inspection are welds e.g. longitudinal and circumferencial welds on pressure vessels and circumferencial welds on pipes. In the

course of time the accuracy and reliability of ultrasonic methods has increased. However, the inspection of components with complicated geometries must be additionally considered by the practical application of new ultrasonic systems. Such complex geometries are e.g. the spherical bottom or dome [1-4] of a reactor pressure vessel, the nozzle inner radius [5,6] or the welds between the bottom and the pump nozzles [7]. Many of these geometries have a very reduced accessibility for ultrasonic probes.

For such problems *PHASED-ARRAY PROBES* can be used with advantage [8]. Therefore, a lot of experiments have been carried out to adapt this technique in practical conditions.

This paper describes the principles of phased array probes, the ultrasonic equipment for the generation of the transmitter pulses and the application of the whole system for data acquisition and data evaluation.

#### Phased-Array System

Phased-array probes are special ultrasonic probes with electronically steered sound fields. This can be compared with the well known radar (radio detecting and ranging) system. This special kind of sound field steering can be achieved by a number of single piezoelectric crystals i.e. a number of elements as shown in Fig. 1. With a linear delay-time between the different transmitter pulses an inclined sound field would be generated. A variation of the angle of refraction requires a variation of the linear distribution of the delay-time. With a delay-time like a curvature of a lens, a focussed sound field is generated at a certain distance from the elements. The distance depends on the radius of the curvature and therefore on the delay-time distribution. Changing this distribution electronically, the focal distance is also changing as in the well known optical lens zoom effect. Both linear and curvature delay-time distributions can be changed together with a speed equal to the actual sound velocity.

In order to realize this sound field steering, the equipment called Phased-Array Equipment was developed in the laboratory for Ultrasonic Testing at the Federal Institute for Materials Research and Testing (BAM) in cooperation with Siemens. Figure 2 shows the sixteen channel configuration controlled by a personal computer in an experimental arrangement in the laboratory. The phased array equipment can be connected to four phased-array probes with 16 elements each. Together with a manipulator (see also Fig. 2) for the probe movement, the above-mentioned complex geometries can be inspected. However, the manipulator must be adapted to the geometry of the area under inspection. A further advantage of the system is given by the digitization procedure of an A-scan [9]. Typical A-scans digitized from rectified A-scans are shown in Fig. 3. The principle of the digitization procedure as shown in

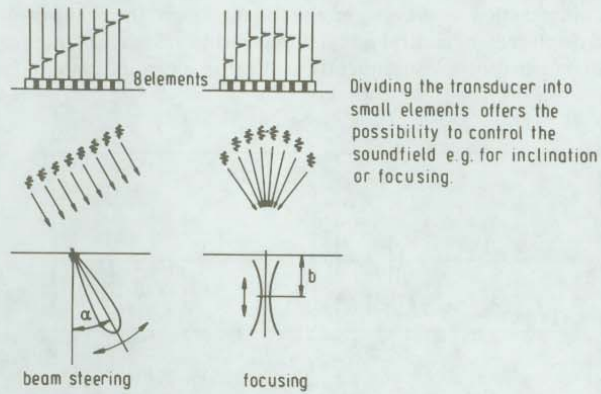


Fig. 1. Principle and Possibilities of Phased-Array probes



Fig. 2. Phased-Array equipment

Fig. 4 can be used, but for usual hard discs with a storage capacity of about 100 MBytes, a low sample rate is necessary because the data received on the previously mentioned components are extensive. For a fast practicable system these conditions are given by the so called pixelized A-scan. The pixelized A-scan together with the

actual angle of refraction or skewing angle, the used gain, the probe position given by the digital displacement control unit, and the sound velocity etc. are stored at the hard disc. All information is consequently available for further evaluations.

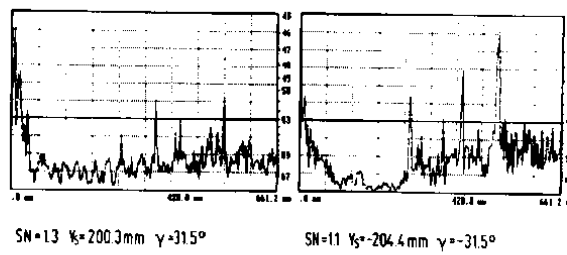


Fig. 3. Symmetrical A-scans with and without indication

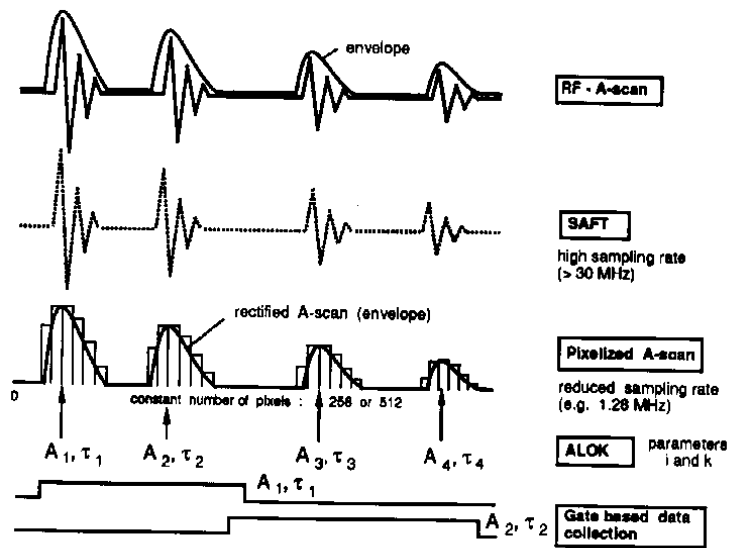


Fig. 4. Evaluation and storage of A-scans

### Experimental Results

For the evaluation of the pixelized A-scans, a lot of software was developed. The examples below show the measurements on the complex geometries in relation to ultrasonic methods and demonstrate some of the capabilities of the phased array system.

The spherical bottom of a boiling water reactor pressure vessel must be inspected from the outside because the core where the fuel elements are kept, is not removable. Existing safety regulations require the inspection of the inner surface. Several assumed cracks as shown in Fig. 5 which may have longitudinal, transverse and diagonal orientations between the neighbouring nozzle tubes. The ultrasonic probes for the inspection of the inner surface can only be guided along paths which are free from instrumentation nozzles. In order to check all possible crack orientations, an inspection system is needed which is fully controlled by a computer program during the phased array probe movement. An equivalent geometry in the dome of the pressurized water reactor pressure vessel is shown in Fig. 6.

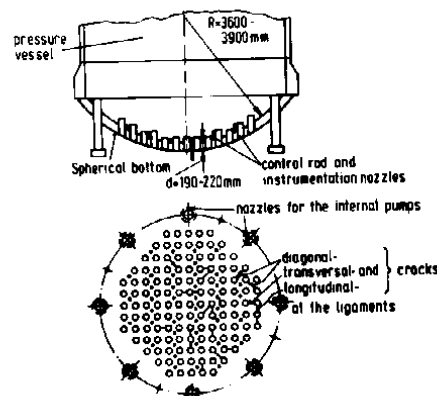
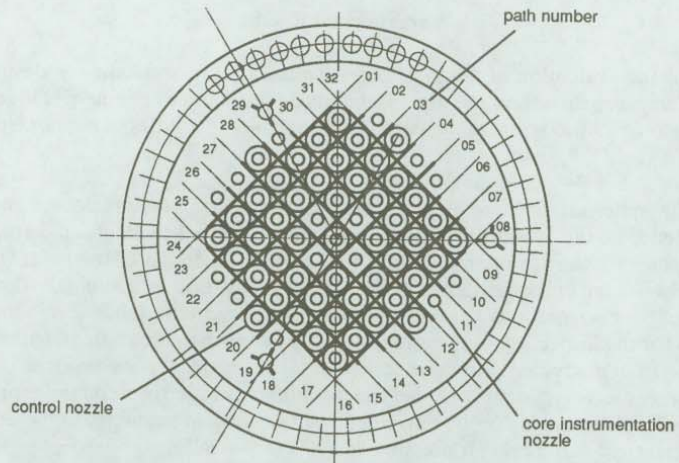
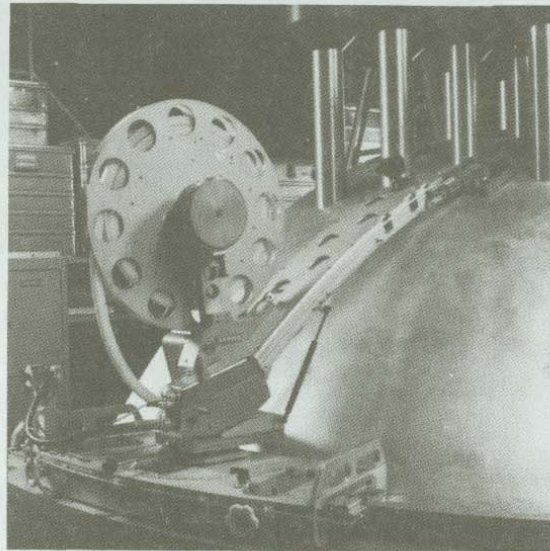


Fig. 5. Assumed cracks at a spherical bottom of a BWR

The probe movement is supported by a manipulator. In the case of the dome inspection, the manipulator device on a dome mock-up is shown in Fig. 7. The manipulator is controlled by a microprocessor. This unit is approximately 200m away from the manipulator itself. Therefore for visual control of the movement, a video camera is installed in front of the probes. The use of such a manipulator is necessary because the radiation level must be taken into account and the evaluation of the data received depends on the probe position.



**Fig. 6. Geometry of pressure vessel dome**



**Fig. 7. Manipulator for the pressure vessel dome inspection**

The computer program used must execute the following features:

Calculation and determination of the needed angle of refraction as a function of probe position. For the special geometries like the bottom or dome and also the skewing angle must be calculated as a function of the probe position. All the values are listed and stored for the measurement in so called look-up tables. A graphic representation is shown in Fig. 8. The curves in the diagram show that the needed angle of refraction depends on the skewing angle of the different paths. During the measurement procedure, the program must carry out the variation of the delay-time distribution.

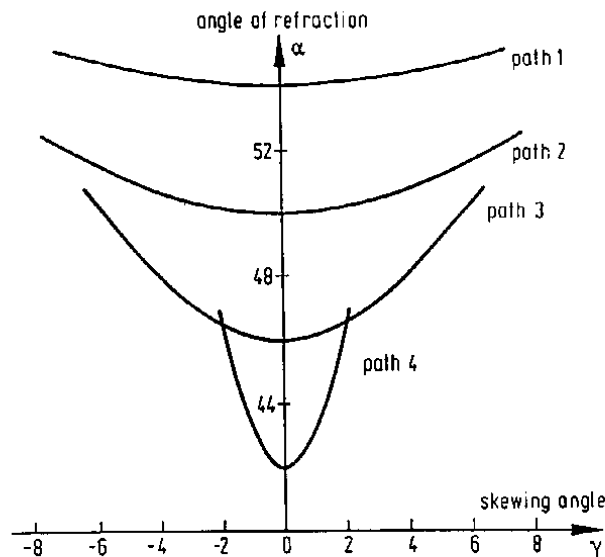


Fig. 8. Refraction angle as a function of the skewing angle

Figure 9 represents a so-called td-scan (time displacement) measured at a notch in a heavy steel test block. One axis represents the time axis, equal to the sound path of the A-scan and the other, the coordinate of the probe displacement. The notch was machined through the cladding material in the base material and had a depth of 100mm and a length of 50mm. The thickness of the austenitic cladding was 7mm and the whole thickness of the steel testblock was 180 mm. With this kind of representation and estimation of the time-of-flight, calculation of the defect position can be carried out. The reflectivity behavior would be determined with the help of the well-known GDS (distance-gain-size) diagram.

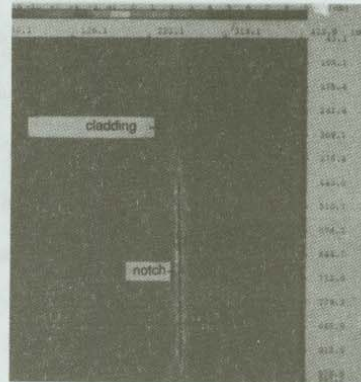


Fig. 9. TD-scan from a Notch

This kind of data representation and analysis was used for the inspection of bottom and dome of a reactor pressure vessel as shown in Figs. 10 and 11. The example in Fig. 10 was obtained on the bottom of research pressure vessel with a scale of 1:1. The evaluation of the symmetrical td-scan is very easy and is based on a visual pattern recognition. Comparing both the td-scans, it is clear that the upper scan has a different pattern in the middle of the picture than the lower scan. During the inspection of the pressure vessel dome of a nuclear power plant in the Federal Republic of Germany, the td-scan shown in Fig. 11 has been obtained.

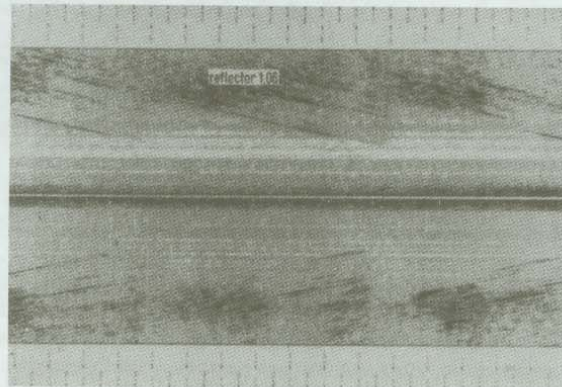


Fig. 10. Symmetrical TD-scans from the test-bottom



Fig. 11. TD-scan from the pressure vessel dome

The interpretation of this image is very easy if the geometry is known well. The noise from the cladding can be clearly separated from the geometric indications and that which came from defect indications.

In the above example the application of td-scans for data presentation in an image form enables very fast outputs because only a few calculations need to be carried out. Therefore, in practice, the preliminary data evaluation is given by the td-scan images.

In a situation where a circumferential movement of the phased array probes around the object is possible, the data analysis can be done by using tomographic methods. The application of the pulse-echo-technique reduces the well-known calculation procedure due to the fact, that the time-of-flight can be measured. To obtain illustrations as shown in Fig. 12, the following procedure is used.

The pixelized A-scans are stored in a pixel net adapted to the geometry where the probe is moved. During the probe movement, a variation of the angle of refraction or skewing angle takes place. Therefore most of the pixels in the net are hit more than once and the "old pixel information" is added to the "new pixel information". After a whole circle, every pixel net value is divided by the number of the hits. The image so received is called an ECHO-TOMOGRAM. This advanced tomographic data analysis was coupled with the inspection of the nozzle inner radius at the boiling water reactor with the inspection of the nozzle inner radius at the boiling water reactor (BWR) feedwater nozzle from the outside. The geometric problem as shown in

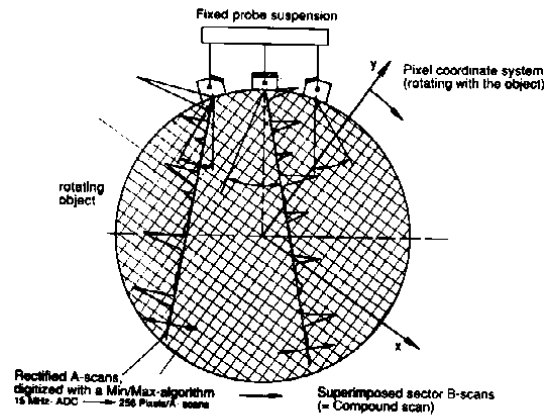


Fig. 12. Echotomography for turbines

Fig. 13 represents the cross section of the nozzle. For the detection of cracks at the inner radius of the nozzle, the phased array probe must be coupled on the outer surface of the pressure vessel at a distance from the center-line of the nozzle. The skewing angles are changed in the range between  $+14^\circ$  and  $+30^\circ$  and  $-14^\circ$  and  $-30^\circ$  respectively with steps of  $1^\circ$ . The pixelized A-scans thus received are stored in the pixel net as previously described. With a pulse repetition frequency of about 200 Hz the data quantity is about 2MByte for each revolution. An example of an echotomogram obtained on a mock-up with 1:1 scale and artificial defects is shown in Fig. 14.

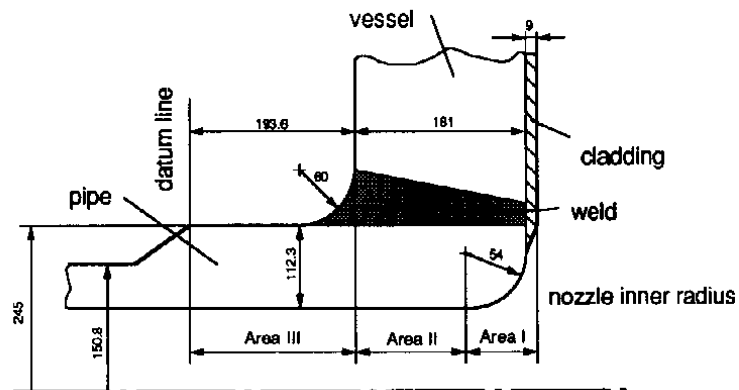


Fig. 13. Feedwater nozzle (cross-section)

The defect indication given in the image by intersections can be clearly separated from disturbed indications e.g. indications from the cladding.

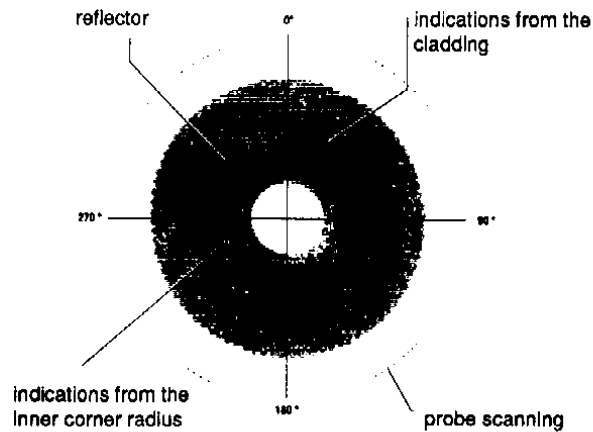


Fig. 14. Echotomographic reconstruction

For the determination of the defect position in the axial direction and the defect length, more than one scan (usual ten), must be carried out with different distance between the probe index point and the nozzle center-line. By superposition of the images received from each scan, the defect length is given by the distance between the intersections of the shortest and largest distance from the center-line of the nozzle. This procedure is automatically done by a computer program. Using this technique, it is therefore possible to determine the most significant parameters, i.e. defect position and the size of the defect, which help in the calculation of the life-time or life-time extension of components.

### Conclusions

The examples of the application of phased-array techniques have shown that some practical non-destructive inspection problems can be solved, especially on components of complex geometries. The application of the phased-array techniques has contributed to the safe operation of nuclear power plants by inspection of such geometries. The image representation of the results, td-scan, or in the manner of the echotomographic image, is very helpful for the inservice inspection of nuclear plant components. This is possible due to the fact that differences in the pattern of the images can be easily recognized by visual inspection.

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### تطبيق الأشعة فوق الصوتية بطريقة الأطوار المصفوفة أثناء استمرار تشغيل الجهاز عند الفحص

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ملخص البحث. تعطى هذه الورقة فكرة مختصرة عن الاستخدامات الحديثة للموجات فوق الصوتية في الفحوصات باستخدام طريقة نظام الأطوار المصفوفة. وقد تم مناقشة نتائج التجارب بعد تطبيق هذا النظام في المجال النووي، وخاصة القياسات التي أجريت على الأشكال الهندسية والتي تعتبر معقدة إذا ما تم استخدام الفحص بواسطة الأشعة فوق الصوتية. وقد تم التركيز على الجزء السفلي والعلوي المقيب أو قطر الفتحة الداخلية من أوعية الضغط المستخدمة في المجال النووي. وقد أخذ في الاعتبار كي تحمل مشكلة الفحص أنه يلزم تخفيض عدد مجسات الأشعة فوق الصوتية المعروفة، وزيادة على ذلك تم شرح المعلومات الأولية المتحصل عليها وتقويمها.