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Development of the Automated Ultrasonic Flaw Detection System for HWR Nuclear Fuel Cladding Tubes

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중수로형 핵연료 피복관의 자동초음파탐상장치 개발

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Abstract

An automated ultrasonic flaw detection system was developed for thin-walled and short tubes such as Zircaloy-4 tubes used for cladding heavy-water reactor fuel. The system was based on the two channels immersion pulse-echo technique using 14 MHz shear wave and the specially developed helical scanning technique, in which the tube to be tested is only rotated and the small water tank with spherical focus ultrasonic transducers is translated along the tube length. The optimum angle of incidence of ultrasonic beam was 26 degrees, at which the inside and outside surface defects with the same size and direction could be detected with the same sensitivity. The maximum permissible defects in the Zircaloy-4 tubes, i.e., the longitudinal and circumferential v notches with the length of 0.76 mm and 0.38 mm, respectively and the depth of 0.04 mm on the inside and outside surface, could be easily detected by the system with the inspection speed of about 1 m/min and the very excellent reproducibility. The ratio of signal to noise was greater than 20 dB for the longitudinal defects and 12 dB for the circumferential defects.

요 약

중수로형 핵연료의 피복재로 사용되는 Zircaloy-4 관의 결함검사를 위한 자동초음파 탐상장치가 개발되었다. 이 장치에는 중심진동수가 14 MHz이고 대역폭이 11 MHz인 집속 초음파 펄스를 사용한 수침 펄스-에코우 탐상기술과 특별히 고안된 시험수조 이송식 초음파주사기술이 적용되었다. 같은 크기와 방향을 갖는 관내외면 결함들을 같은 높이의 초음파 신호로 검출하기 위한 초음파 빔의 최적입사각은 26도이었다. Zircaloy-4 피복관의 최대 허용 결함인, 깊이가 관두께의 10%인 0.04 mm이고, 길이가 0.76 mm인 축방향 및 길이가 0.38 mm인 원주방향 V형 인공결함들이 관내외면에 개재된 표준시험관을 사용하여 이 장치의 성능시험을 수행하였다. 그 결과 인공 표준시험관내의 모든 결함들을 매우 우수한 재현성을 갖고 분당 약 1 m의 속도로 검출할 수 있었으며 이때의 신호 대 잡음 비는 축방향 결함에 대해서는 20 dB, 원주방향 결함에 대해서는 12 dB 이상이었다.

I. Introduction

Uranium dioxide pellets in water-cooled reactors are usually encapsulated in the tubes made of zirconium alloy which have very low neutron absorption cross-section. In order to improve the neutron economy it is desirable to use as thin tubes as possible. On the other hand, sufficient strength of the cladding tubes must be ensured, because the cladding tubes are subjected to various stresses such as thepressure of the fission gases, heat gradients, pellet swelling and neutron bombardment in reactor. Besides, the gap between the pellets and the canning must lie within tolerance limits in order to achieve optimum heat transfer characteristics. The fulfilment of these stringent requirements can only be achieved if the tubes are produced defect-free and to very exact dimensional specifications. Table 1 shows a typical example of the specification for Zircaloy-4 tubes used in heavy-water reactors. To ensure that the cladding tubes fulfill these strict dimensional and quality requirements, a reliable and fast 100% inspection must be performed. At present, the immersion pulse-echo method using focused ultrasonic transducers is the most suitable method of testing the cladding tubes for these kinds of measurements (1)-(2).

The automated ultrasonic flaw detection system for the cladding tubes was developed as a part of the localization project of heavy-water reactor fuel. In this paper, the inspection principles and equipments of the system were described and the inspection capacity and accuracy was evaluated.

II. Inspection Principles

In the immersion ultrasonic testing of thin materials, the following wave types can generally be used for detecting defects: Shear waves, Surface waves and Lamb waves. Surface waves have small penetration depth and are damped rapidly in surrounding liquid. Therefore, if possible, this type of waves should be avoided during the testing of tubes where inside and outside defects should be detectable with the same sensitivity. Lamb waves can only be generated and propagated in thin material. Their production is dependent on the angle of incidence as well as the product of the material thickness, t, and the frequency, f, of the incident waves. Moreover Lamb waves have a number of symmetric and antisymmetric modes. However, only the zeroth order symmetric mode below the cut-off frequency of the first order symmetric mode ($f=C_T/t$) is usually used for detecting defects. The velocity of the mode is equal to about $\sqrt{2}$ times the velocity, G, of shear waves (3). Then the wavelength of Lamb waves which can be used for detecting defects in thin materials is greater than $\sqrt{2}$t. And this type of waves do not have enough sensitivity and resolution to detect the maximum permissible defects illustrated in Table 1. Therefore shear waves were used in the automatic ultrasonic flaw detection system developed for Zircaloy-4 tubes used for cladding heavy-water reactor fuel. The wavelength of the shear waves to be used must be shorter than half length of the maximum permissible defects.

Fig. 1 shows an alignment between tube and transducers for detecting longitudinal and circumferential defects in a cladding tube. The channel 1 is for longitudinal defects and the channel 2 for circumferential defects. The angle of incidence, Θ_i, must be greater than the first critical angle, Θ_{1c}, and be less than the second critical angle, Θ_{2c}, in order to produce only shear waves in the tube-wall. These critical angles are given by Snell's law:

$$\Theta_{1C}=\mathrm{Sin}^{-1}(C_W/C_L),\quad \Theta_{2C}=\mathrm{Sin}^{-1}(C_W/C_T),$$

where C_W is the sound velocity in water at room temperature (about 1480m/sec) and C_L and C_T is the velocity of longitudinal and shear waves in the tube wall, respectively. The velocities vary with

Table 1. Specification for Zircaloy-4 cadding tubes in heavy-water reactors

Type of inspection	Parameter to be checked	Dimensional limits or inspection requirements
Dimensional control	Outer diameter	13.08±0.030 mm
	Wall thickness	0.42±0.030 mm
	Inner diameter	12.24±0.030 mm
	Eccentricity*	0.050 mm
	Ovality**	0.050 mm
Defect inspection	Longitudinal defects in tube wall	Minimum length=0.76 mm Depth=10% of the wall thickness Minimum length=0.38 mm Depth=10% of the wall thickness

* Eccentricity=max. thickness-min. thickness at any circumference.
** Ovality=max. outer(inner) diameter-min. outer(inner) diameter at any circumference.

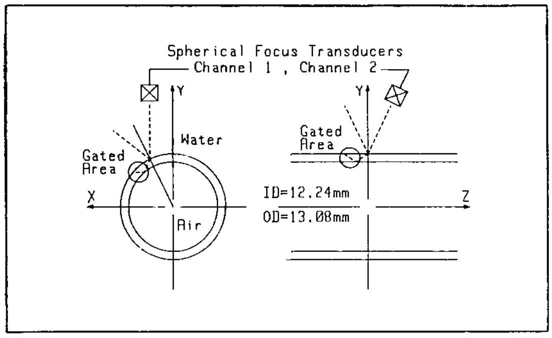


Fig. 1. Alignment Between Tube and Transducers for Detecting Longitudinal and Circumferential Defects in a Cladding Tube.

material of alloys or manufcturing history. The velocities of longitudinal and shear waves in Zircaloy-4 used in heavy-water reactors were about 4540 m/sec and 2440 m/sec, respectively. As shown in Fig. 1, the inside and outside defects on a cladding tube are measured by half skip and one skip echoes, respectively. This has been done in order to eliminate the higher sensitivity to outside defects due to direct reflection. The most suitable angle of incidence is experimentally determined with the help of the inside and outside reference notches. At the optimum angle of incidence, the half skip echo from the inside notch and the one skip echo from the outside notch with same size and direction should have the almost same amplitude. In the ultrasonic flaw detection system developed for Zircaloy-4 tubes used for cladding heavy-water reactor fuel, the optimum angle of incidence was 26 degrees and then the angle of refraction for shear waves was 46 degrees.

While a cladding tube is scanned by the specially developed ultrasonic scanner, the gate-pulse is positioned so as to avoid the direct reflection echoes from outside defects and to select only the half skip and one skip echoes. And then the output signals of the peak detector which measures the peak amplitude of the gated echo are recorded on a strip chart. The quality of the cladding tube is evaluated by comparision of the inspection record with that for the reference cladding tube containing the maximum permissible defects on inside and outside surface.

III. Inspection Equipments

1. Ultrasonic Flaw Detectors and Transducers

In the automatic testing of thin-walled tubes by

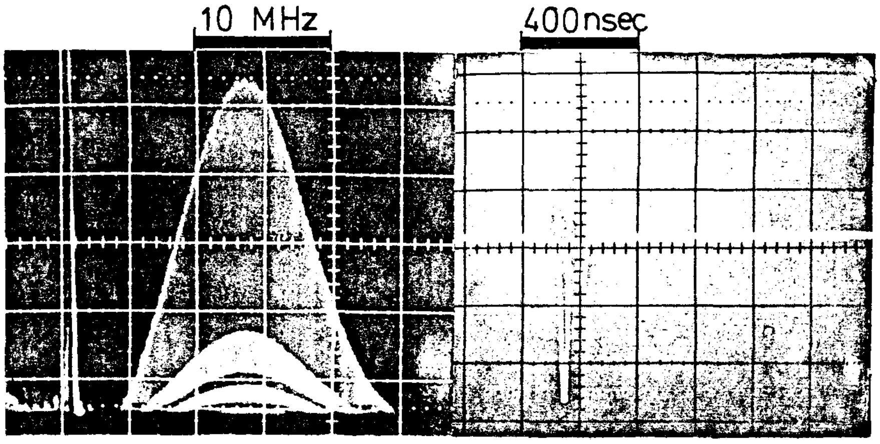


Fig. 2. Frequency Spectrum and Real Time Waveform for an Ultrasonic Pulse Used in the System.

immersion pulse-echo method using shear waves, the ultrasonic flaw detectors and transducers should have the capability to seperate the half skip echoes by inside defects from the direct reflection echoes by outside defects with very high sensitivity. If not, because the gate-pulse can not be positioned so as to avoid the direct reflection echoes and to select only the half skip and one skip echoes, the outside defects may be overestimated. The time difference between the half skip echo and the one skip echo for the heavy-water reactor fuel cladding tubes is about 500 nsec ($\approx 2S_{1/2}/C_T$), where $S_{1/2}$ is the half skip distance of shear waves propagating in the tube wall at the angle of refraction of 46 degrees. Therefore the ultrasonic flaw detectors and transducers which can be used for inspection of the cladding should have enough sensitivity and resolution to detect the maximum permissible defects with depth of 0.04 mm and length of 0.38 mm and to seperate the half skip echo with the time delay of about 500 nsec from the direct reflection echo.

Fig. 2 shows the real time waveform and frequency spectrum for an ultrasonic pulse generated by the ultrasonic flaw detectors and transducers used in this system. Because the frequencies below 5 MHz which is the cut-off frequency of the first order symmetric mode of Lamb waves ($f = C_T/t$) are not contained, the disturbance of Lamb waves can be avoided. In addition, because of the high central frequency of 14 MHz and wide frequency band-width of 11 MHz for 6 dB down amplitudes, the pulse have a very narrow time-width of 100 nsec for 6 dB down amplitudes and no internal ringing signals of the transducer. The internal ringing of transducer is generally a principal cause of poor resolution. In order to avoid any disturbance from another type of waves and to achieve a good sensitivity for very small defects, it is necessary to limit the dimensions of the incident ultrasonic beam. Furthermore, it is important that the intensity of the incident beam is well defined and evenly distributed over the area where it strikes the tube. This is best achieved by use of focused transducers. The focal distance of our transducers measured by using a steel ball reflector with 6mm diameter in water was 29 mm, the beam diameter at the focal point was 0.6 mm for 6 dB down amplitudes, and the maximum pulse repetition rate of the ultrasonic flaw detectors was 5 KHz.

2. Ultrasonic Scanner

The ultrasonic scanner provides an accurate helical scan over the length required for 100% ultrasonic inspection of a cladding tube. The helical scan is usually obtained by two methods. In the first method, a test water tank and transducers are fixed and a tube to be tested is rotated and trans-

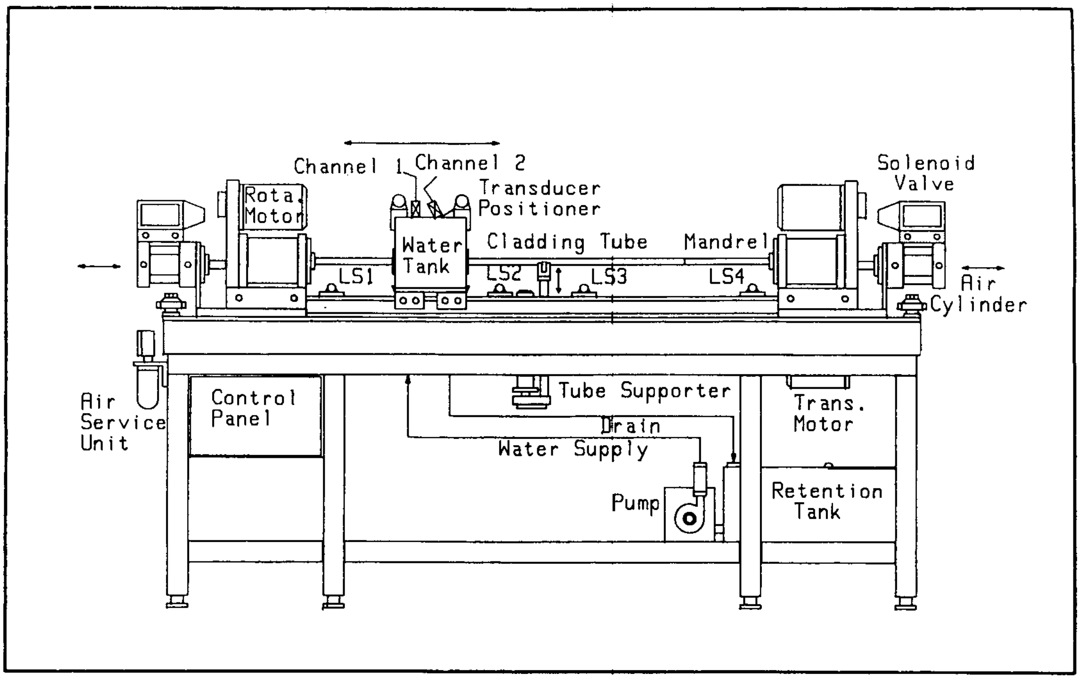
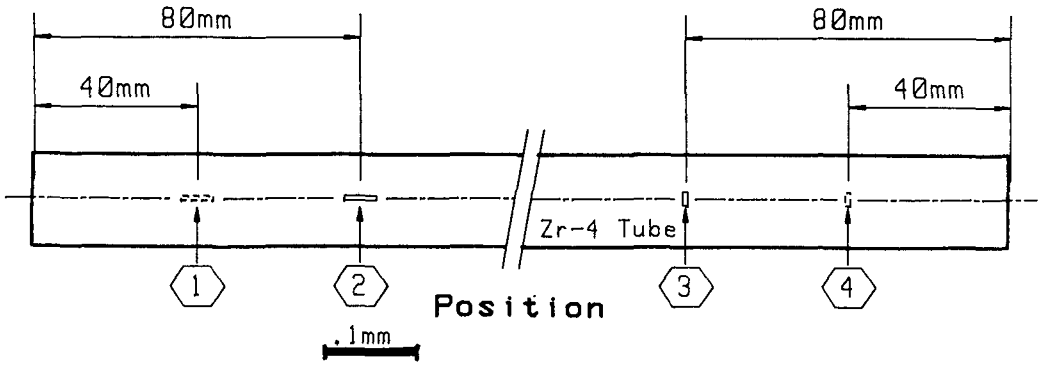
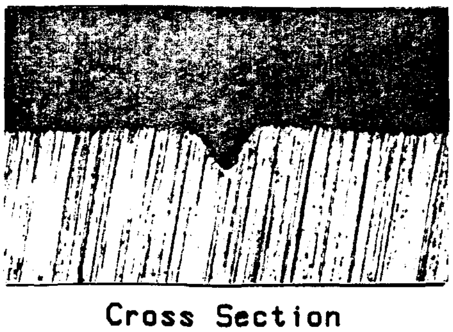


Fig. 3. Cross Sectional View of the Ultrasonic Scanner Developed at KAERI Using a Test Tank Translation Technique.

lated by means of rubber wheels (1). In the other method, a water chamber with transducers is rotated and a tube to be tested is only translated (2). In both methods, if the length of a tube to be tested is not greater than twice the distance between two rubber wheels adjacent to the test water tank, the plastic stopper connecting tubes for continuous inspection and/or preventing the entry of water into the tube as it pases through the water tank may not fulfill its function. Then, the inspection reliability is greatly decreased. Therefore the special helical scanning technique in which the tube to be tested is only rotated and the test water tank is translated along the tube length was used in the ultrasonic scanner for the heavy-water reactor fuel cladding tubes with the short length (about 500 mm).

Fig. 3 shows a cross sectional view of the developed ultrasonic scanner. With the test water tank at the end position, a cladding tube to be tested is placed between the mandrels and on the tube supporter, and grasped on the inner surface by rubber O-rings mounted on the end of the mandrels. The mandrels are mounted on the slides which allow the mandrels to move a sufficient distance for the cladding tube to be grasped by or free from the rubber O-rings. These slide movements are accomplished by air cylinders controlled by electric solenoids. The cladding tube is rotated by the induction motors coupled to the mandrels. And the translation motor is coupled to the lead screw which drives the test water tank in either direction. While the cladding tube is rotated, the test water tank is translated from the limit switch 1(or 4) to the limit switch 4(or 1). The rotation and translation speeds can be changed by the revolution speed of the motors. The maximum revolution speed of the motors is 1700 rpm. The mechanical manipulators attatched at side walls of the test water tank adjust transducer-positioning to achieve the optimum angle of incidence and tube-transducer distance. The cladding tube pases





No	Notch	Depth (mm)	Length (mm)
1	Longi. Inner	.039	.76
2	Longi. Outer	.040	.76
3	Trans. Outer	.042	.38
4	Trans. Inner	.038	.38

Dimensions

Fig. 4. Specification for Reference Tube Used for Calibration and Porformance Test of the Developed Ultrasonic System.

through the small test water tank through O-rings mounted in ball bearings which rotate with the tube. This technique minimizes wearing of the cladding tube, rigidly supports the cladding tube to achieve accurate ultrasonic alignment and allows little water leakage. Any water that does leak is collected, filtered and recirculated through the retention tank. Since the test water tank is positioned over a mandrel at the start and the end of each test, the cladding tube can be exchanged without draining water from the test water tank.

IV. Performance Test of the System

Any nondestructive testing equipment must be calibrated by use of the reference standard containing simulated defects, by which not only the sensitivity of the inspection can be determined but also criteria for rejection of faulty products can be established. The reference standard must be made from material of the same size, finish and metallugical condition as those being inspected. The calibration of the ultrasonic system developed for detecting defects in cladding tubes consists of establishment of the relationship between the signal obtained from the ultrasonic flaw detector and size of the defect, and determination of the height of the singal that corresponds to the maximum permissible defect shown in Table. 1.

Fig. 4 shows the locations, dimensions and cross section of the artificial notches on the reference cladding tube used for calibration and performance test of the developed ultrasonic system. The artificial notches were produced by punching method with special tool. The dimension measurements of the defects were nondestructively performed by use of an optical microscope. The depth of the outside notch was directly measured

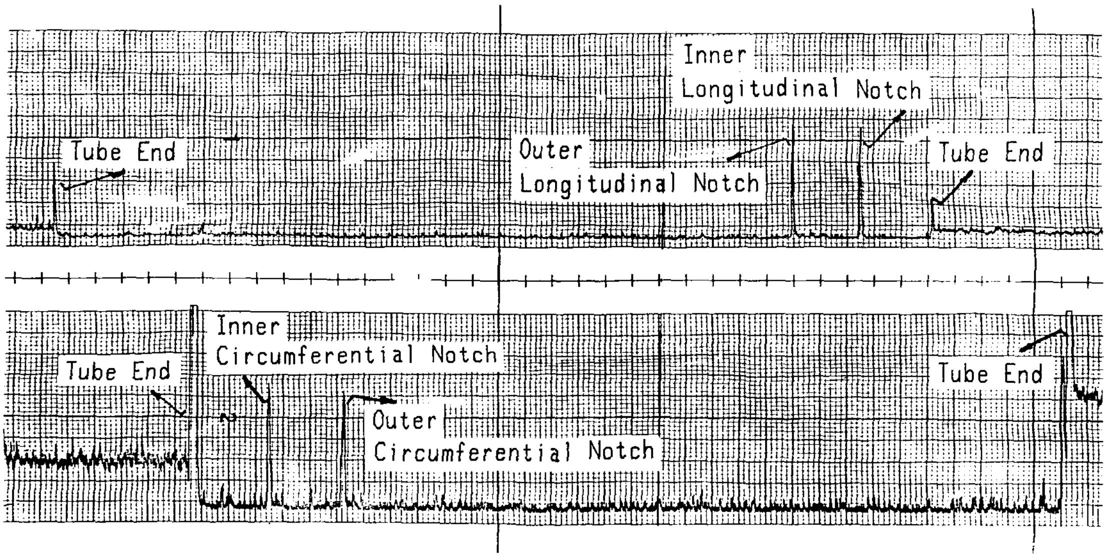


Fig. 5. Forward Inspection Record for Reference Tube(x Axis=5 div/sec, y Axis=20 mV/div).

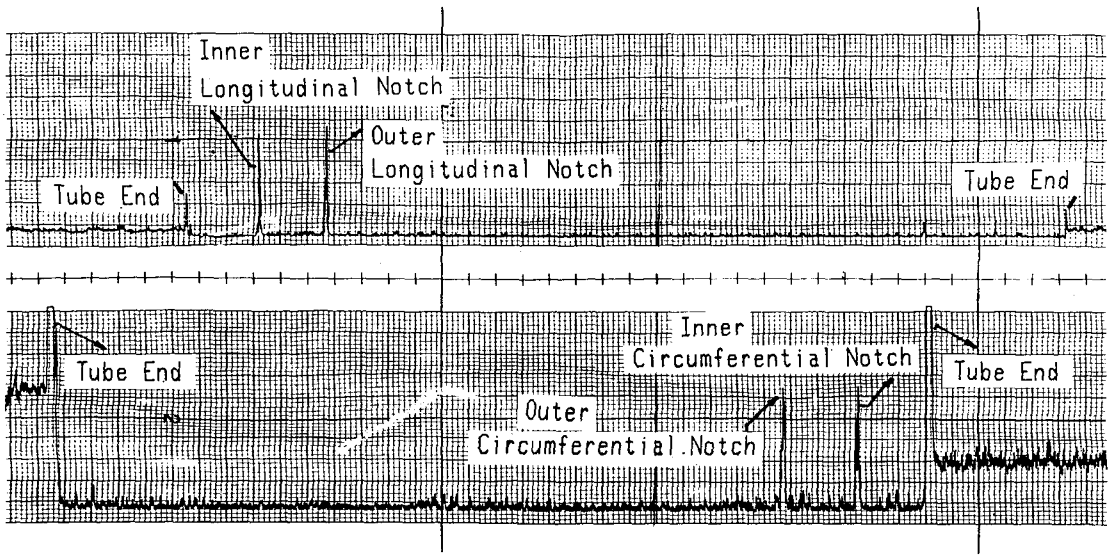


Fig. 6. Backward Inspection Record for Reference Tube(x axis=5 div/sec, y axis=20 mV/div).

by the double focusing technique (focusing on the bottom of the notch and on the tube surface). But the direct measurement for the inside notch was impossible. Thus the depth of the inside notch was indirectly measured with the replica method by which the inside notch could be measured in the same way as for the outside notch.

Fig. 5 shows the inspection record for the reference cladding tube. In this inspection, the maximum revolution speed of 1700 rpm, the maximum pulse repetition rate of 5 KHz and the test tank translation speed of 0.9 m/min were employed. And the difference of attenuation settings between two ultrasonic flaw dectors was 6 dB.

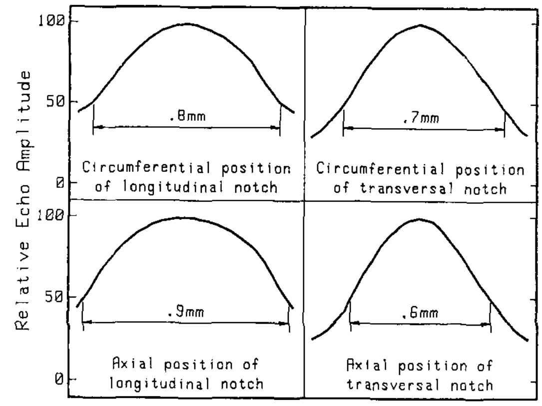


Fig. 7. Practical Variation of Defect Echo Amplitude in an Inspection Unit Cell.

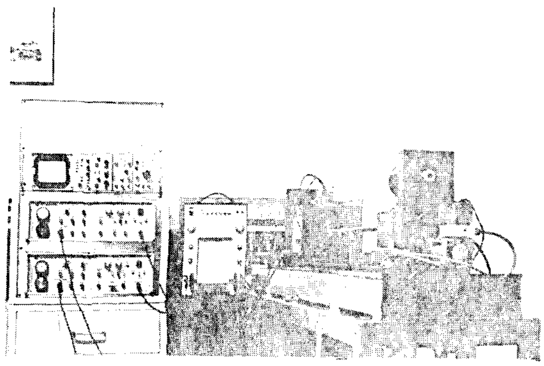


Fig. 8. Overall View of the Automatic Ultrasonic Flaw Detection System for HWR Nuclear Fuel Cladding Tubes.

These inspection parameters produce a helix pitch of 0.54 mm advance per revolution and an ultrasonic pulse for each 0.23 mm of tube surface passing the transducers in the test water tank. Since the diameter of the ultrasonic beam used in this system was 0.6 mm for 6 dB down amplitudes, this scanning condition can be considered as equivalent to total surface scanning. Fig. 6 shows the record obtained by inspecting the reference tube in the opposite direction with the same scanning condition as the previous inspection. It can be seen that all four defects on the reference cladding were detected with the very excellent reproducibility; the two longitudinal defects in the channel 1 and the two circumferential defects in the channel 2. In addition, the inside and outside defects with the same size and direction were detected with the almost same sensitivity. And the signal from the longitudinal reference notches had the almost same height with that from the circumferential reference notches. Considering the 6 dB difference of attenuation settings between two ultrasonic flaw detectors, the signal height can be linearly related with the size of defect. Without using additional filter and amplifier to eliminate noises and to amplify defect signals, the ratio of signal to noise obtained was above 20 dB for the channel 1 and 12 dB for the channel 2. Thus we believe that discontinuities down to 5% of the tube wall-thickness in depth with 0.38 mm in length can be easily detected by the developed ultrasonic system.

The practical inspection pattern forms a net on the tube to be tested. The size of mesh corresponding to inspection unit cell is determined by the pulse repetition rate along the circumference of the tube and by the pitch in the inspection spiral along the tube axis. The defect echo amplitude will vary with the position of the defect within an inspection unit cell in the net. The highest accuracy requires minimum difference between the maximum and minimum amplitude of the defect echo, i.e., small inspection unit cell. However, since the smaller inspection unit cell corresponds to the slower inspection speed, a compromise must be made between the size of inspection unit cell, the capacity and economy of the inspection procedure. A practical variation of the defect echo amplitude in an inspection unit cell is shown in Fig. 7. This was obtained by slightly turning the reference tube and moving it slightly in the axial direction from the position at which the one skip echo from outside reference notch have the highest amplitude. During practical inspection of tube the inspection unit cell for both channels is identical. And the variation of the echo amplitude by circumferential defects is greater than that by longitudinal defects. As mentioned in previous paragraph, the sample scannings of the reference cladding produced the inspection unit cells with the size of 0.54 mm by 0.23 mm. And then the variation of defect echo amplitude along the cirumferential position in the inspection unit cell can be negligible in both channels. Therefore the variation of defect echo amplitude will be less than 2 dB and 5 dB for the channel 1 and 2, respectively. The variations of the defect echo amplitues can be easily permissible since the ratio of signal to noise in the scannings was above 12 dB. With the amplitude variation of a defect echo less than 6 dB, the maximum inspection speed applicable in this system is about 1 m/min(= 0.6 mm ∗1700 rpm).

V. Summary and Conclusion

Developed was the automated ultrasonic flaw detection system for Zircaloy-4 tubes used for cladding heavy-water reactor fuel. The overall view of this system was shown in Fig. 8. The system was based on the two channels immersion pulse-echo technique using 14 MHz shear wave and the specially developed helical scanning technique, in which the tube to be tested is only rotated and the small water tank with the spherical focus ultrasonic transducers is translated over the length as required for 100% ultrasonic inspection of the tube. The optimum angle of incidence of ultrasonic beam at which the inside and outside surface defects with the same size and direction could be detected with the same sensitivity was 26 degrees.

The calibration and performance test of this system was accomplished with use of the reference cladding tube containing the longitudinal and circumferential notches with the length of 0.76 mm and 0.38 mm, respectively and the depth of 40 μm (10% of the tube wall-thickness) on the inside and outside surface. The reference cladding tube was rotated at 1700 rpm and scanned at 0.9 m/min with the pulse repetition rate of 5 KHz. It was shown that all four defects on the reference cladding tube were detected with very excellent reproducibility. In addition, the inside and outside defects with the same size and direction were detected with almost same sensitivity, the ratio of signal to noise was above 12 dB and and the signal amplitude from a defect was linearly related with the size of defect. Thus we believe that discontinuities down to 5% of the tube wall-thickness in depth with 0.38 mm in length could be easily detected by the developed system.

The amplitude of ultrasonic echo by a defect varies with the position of the defect within an inspection unit cell which are determined by the pulse repetition rate along the circumference of the tube to be tested and by the pitch in the inspection spiral along the tube axis. With the amplitude variation of a defect echo less than 6 dB, the maximum inspection speed applicable in the system was about 1 m/min.

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