

## Equivalency Assessment for an Eddy Current System Used for Steam Generator Tubing Inspection

Chan-Hee Cho\*<sup>†</sup>, Tae-Hun Lee\*, Hyun-Ju Yoo\* and Gyoon-Young Moon\*

**Abstract** Eddy current testing is widely used for inspecting steam generator tubing in nuclear power plants (NPPs). The inspection technique for steam generator tubing in NPPs should be qualified in accordance with examination guidelines. When the components of a qualified system such as eddy current tester, probe, and data analysis program, are changed, the equivalency of the modified system to the originally qualified system must be verified. The eddy current tester is the most important part of an eddy current testing system because it excites and transmits alternating currents to the probe, receives coil impedance of the probe and generates signals for anomalies. The Korea Hydro & Nuclear Power Co., Ltd. (KHNP) developed an eddy current testing system with an eddy current tester and data acquisition-analysis program for inspecting the steam generator tubing in NPPs; this system can be used for an array probe and as a bobbin and rotating probes. The equivalency assessment for the currently developed system was carried out, and we describe the results in this paper.

**Keywords:** Equivalency Assessment, Eddy Current Testing, Nondestructive Examination, Steam Generator Tubing

### 1. Introduction

Utilities should use the qualified techniques when performing eddy current tests (ECT) for the inspection of steam generator tubing. The qualified techniques are listed on the performance demonstration database in the form of examination technique specification sheet (ETSS) in the Electric Power Research Institute (EPRI) documents, and their requirements are described in the EPRI steam generator(SG) examination guidelines [1]. The EPRI SG examination guidelines require that each ETSS define essential variables for equipment, technique, and data analysis such as eddy current tester, probe, cable, tube material, acquisition and analysis program, calibration standard, sampling rate, and analysis procedure, etc. Examination techniques with essential variables that vary within the ranges specified in the ETSS are considered equivalent. The KHNP developed an eddy

current testing system for the inspection of SG tubes. This system includes eddy current tester, probe push-puller control system, and data acquisition-analysis program. The eddy current tester is composed of synthesizer, analog processor, and analog-to-digital conversion board. It excites alternating currents, senses coil impedance variation of the probe and produces the eddy current signal. The probe push-puller system is used to move the bobbin, rotating, and array probes for the data acquisition. The acquired data are analyzed by the qualified data analysts using data analysis program in order to identify whether a tube includes flaws [2]. The currently developed data acquisition-analysis programs are based on the Windows operating system, while the previously used programs are on the Unix-based. The equivalency assessment for the currently developed system was carried out and the results were explained in depth in this paper.

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## 2. Equivalency Requirements

### 2.1 ECT System Developed by KHNP

There have been some degradation mechanisms on SG tube walls in the nuclear power plant such as pitting, wear, impingement, and stress corrosion cracking, etc. [2]. For the detection of flaws on tube walls, the eddy current testing is used because it offers a relatively low cost approach for high speed, large scale testing of metallic materials in high pressure and temperature engineering systems. The ZETEC eddy current testing systems [3] like MIZ-70, which were qualified in the EPRI ETSS, have been widely used in many countries including Korea, Japan and the U.S. The KHNP developed an eddy current testing system for the inspection of SG tubes. This system is composed of not only hardware such as fixture controller, eddy current tester and probe push-puller control system as shown in Fig. 1, but also software for data acquisition and analysis.

The remote fixture is installed in the SG chamber for positioning of the probe. The fixture controller makes the probe locate correctly and accurately on the spot of the tube end which is to be inspected based on the test plan. The eddy current tester comprises a central processing unit, a frequency synthesizer, an analog processor, and an analog to digital converter. It performs all testing functions including wide-range frequency generation, in-phase, and quadrature signal digitization. Basic specifications of the KHNP eddy current tester are the same as the MIZ-70, for instance, 10 Hz to 10 MHz of frequency range, 0 to 20 V of drive voltage, 0 to 23 dB of gain, and 16-bit of A/D resolution. Fig. 2 shows the front and rear view of the KHNP eddy current tester and its X-Y axes signals for the calibration standard are shown in Fig. 3.

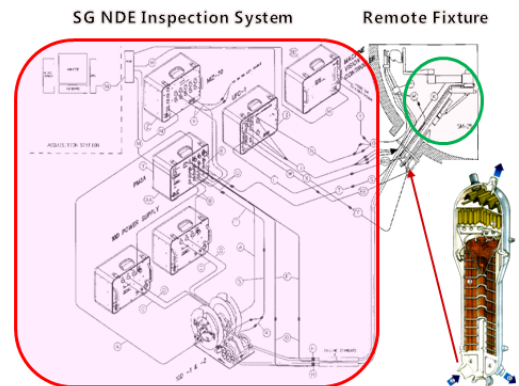


Fig. 1 Eddy current testing system for SG tubing inspection



Fig. 2 Front and rear views of the KHNP eddy current tester

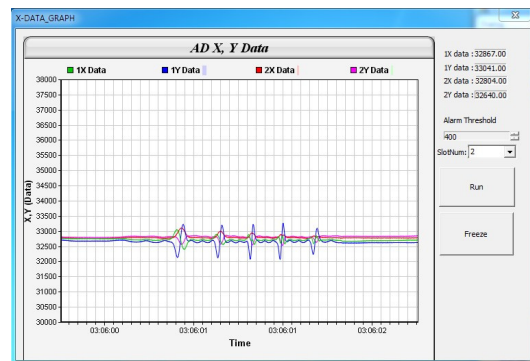


Fig. 3 X-Y signals of the calibration standard obtained from the KHNP eddy current tester

The probe push-puller control system includes motion control circuitry which allows precise control of the probe's travel speed and provides smooth transition between low- and high-speeds without time consuming gear changes. The data acquisition program provides the functions of fixture movement, adjustment of guide-tube location, probe movement, and data

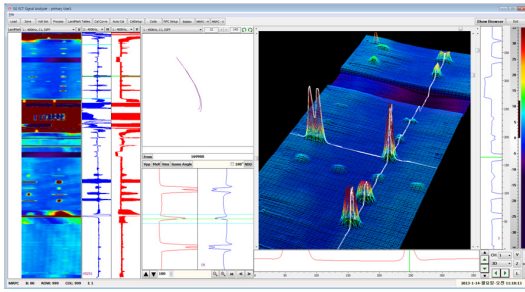


Fig. 4 An example of flaw signals in data analysis program

storage. Flaw detection and sizing for bobbin, rotating, and array probe data can be obtained by analyzing signals from the data analysis program. It also allows the comparison for two separate analysts' results and resolution of their discrepancies [2]. An example of flaw signals from the data analysis program of the currently developed system is shown in Fig. 4.

## 2.2 Equivalency Requirements for Examination Technique

The qualified techniques for SG tube inspection are listed on the EPRI performance demonstration database in the form of ETSS as described above. An ETSS defines essential variables for equipment, technique, and analysis procedure such as eddy current tester, tube material, probe type, probe length, frequency, gain, sample rate, test speed, calibration standard, and data acquisition and analysis programs, etc. When components of a qualified system are changed, verification of equivalency to the originally qualified system must be performed[4]. Examination techniques with essential variables that vary within the ranges specified in the ETSS are considered equivalent. Tolerances were categorized from the EPRI equivalency project are as follows[4]:

For bobbin techniques, (1) The amplitude voltage response from the  $4 \times 20\%$  trough-wall flat-bottom holes (TW FBHs) must be greater

than or equal to 80% of the raw signal response from the qualified technique. (2) All normalized FBH responses must be within  $\pm 40\%$  of the qualified technique. (3) If the tube diameter is the same as that in the qualified technique, then the normalized amplitude voltage response of the 100% deep TW hole must be within  $\pm 40\%$  of the qualified technique. (4) the phase angle responses of the FBH and TW hole flaws must be within 20 degrees ( $\pm 20$  degrees).

For rotating probe techniques, (1) the non-normalized amplitude voltage response from the 100% TW hole by 0.375 inches (9.5 mm) long axial notch must be greater than or equal to 80% of the raw signal response from the qualified technique. (2) All normalized notch amplitude voltage responses (0.375 inches long, ID and OD 40%, 60%, 100% TW) must be within  $\pm 20\%$  of the qualified technique. (3) The phase angle responses of the electric discharge machining(EDM) notches must be within 10 degrees ( $\pm 10$  degrees).

Tolerances for the array probe technique are not established yet, therefore the equivalency assessment for the array probe technique is not included in this paper.

## 3. Assessment Results

The equivalency assessments for the currently developed eddy current testing system (the KHNP system) were performed. The qualified EPRI ETSS 96007.1 for the bobbin probe technique and the ETSS 21410.1 for the rotating probe technique were chosen for the assessments, which have been used in the field inspection of SG tubes in many countries [4]. In this study, the upgraded version MIZ-70 of the MIZ-18 in the qualified ETSS and the KHNP eddy current tester were used for the equivalency assessment. The same essential variables including the probe were used in the assessment except eddy current tester and data acquisition and analysis programs.

### 3.1 Bobbin Probe Technique

The ETSS 96007.1 used in the assessment for the bobbin probe technique has been applied for the detection of inter-granular attack/outside diameter stress corrosion cracking(IGA/ODSCC) at non-dented drilled tube support plates[4]. Table 1 shows the comparison for the essential variables of the ETSS 96007.1 and the KHNP system.

Table 1 Essential variables of the ETSS 96007.1 and the KHNP system

Essential Variables	ETSS 96007.1	KHNP System
Tube Material	I-690	I-690
Tube OD (in)	0.750	0.750
Tube wall (in)	0.043	0.043
Relative current density	22.24@550 kHz 45.61@150 kHz	22.24@550 kHz 45.61@150 kHz
Coil space (in)	0.06	0.06
Probe	Bobbin MR	Bobbin MR
Eddy current tester	MIZ-70	KHNP
Acquisition software	ZAC	KHNP-ACQ
Analysis software	EddyNet	KHNP-ANA
Probe manufacturer	ZETEC	ZETEC
Probe type	MULC	MULC
Fill factor (%)	84	84
Frequency (kHz)	550/150	550/150
Volts/Gain	12/0.5	12/0.5
Sample rate	40	40
Test speed (in/sec)	40	40
Test direction	Pull	Pull
Analysis software	HP c3750	PC
Calibration standard	ASME	ASME

The relative eddy current density is calculated using the following approximation equation:

$$J(x)/J_0 = e^{-x/\delta} \quad (1)$$

where  $J(x)$  is the eddy current density at location  $x$  inside the conducting tube wall and  $J_0$  is the magnitude of the eddy current density on the surface of the tube wall closest to the probe coil. The eddy current skin depth of penetration  $\delta$  is expressed by Eq.(2) as follows:

$$\delta = \sqrt{\frac{2\rho}{2\pi f\mu}} \quad (2)$$

where  $f$  is the operating frequency,  $\rho$  is the electrical resistivity of the material and  $\mu$  is the magnetic permeability of the material.

The bobbin probe and the ASME calibration standard used in the assessment are shown in Fig. 5.

The results of the equivalency assessment for the bobbin probe technique are shown in Table 2 and Fig. 6 to Fig. 11. In Table 2, P\_P uses the peak-to-peak value to calculate both the volts and phase measurement[2]. MxR measures the maximum rate of change for the phase value of small set of vector points in signal[2]. Diff. Mix denotes differential mix of two signals. There are two modes in eddy current testing, absolute and differential mode. An absolute coil

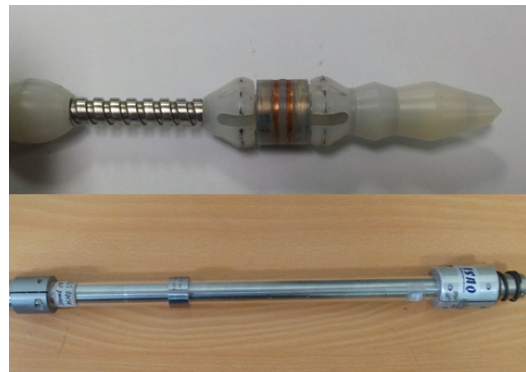


Fig. 5 Bobbin probe and ASME calibration standard

responds to the electromagnetic properties of the test object in the magnetic field of the coil without comparison to response of a second coil. Differential coils are two coils connected in such a way that electromagnetic differences in the regions beneath the coils will cause an imbalance between them to be signaled. A problem of the absolute eddy current probe is the difficulty of detecting small changes in impedance, which are superimposed over the value in air. In addition, changes in the coil parameters because of environmental factors and liftoff can often mask changes due to discontinuities, making signal interpretation very difficult. An alternative to the absolute eddy current probe is the differential eddy current probe. The probe consists of two identical coils mounted on the same axis as the tube but spaced apart by a small distance. The two coils from two arms of a bridge circuit. The bridge imbalance signal is the voltage difference across the impedance of two coils. The mix of two differential signals in different frequencies is

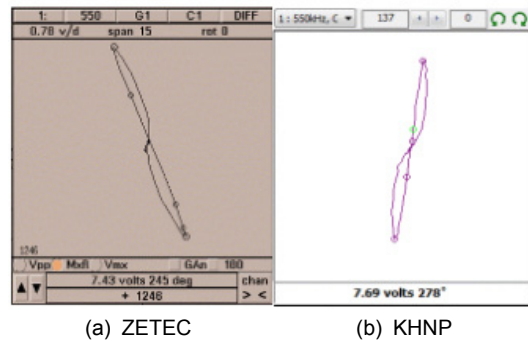


Fig. 6 Raw 550 kHz bobbin differential signals of 4x20% FBHs

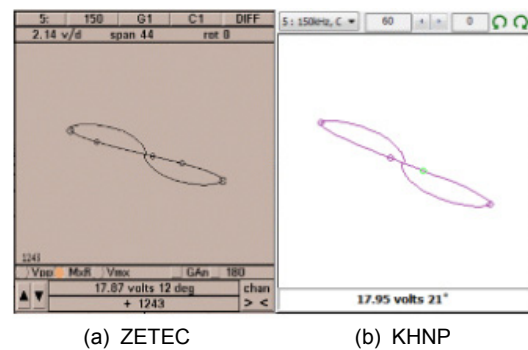
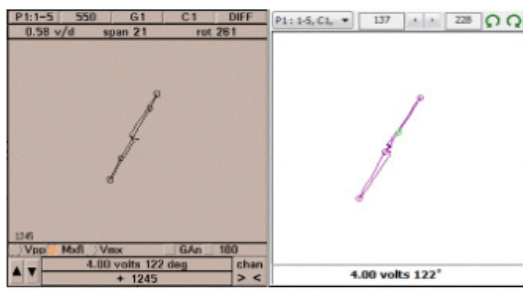


Fig. 7 Raw 150 kHz bobbin differential signals of 4x20% FBHs

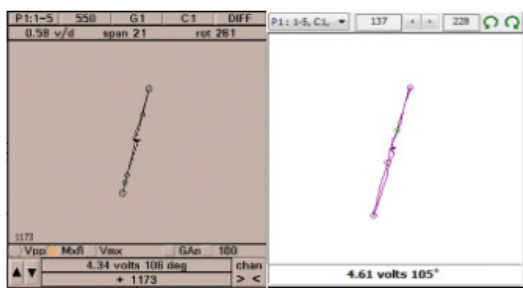
Table 2 Results of the equivalency assessment for bobbin probe technique between the ETSS 96007.1 and the KHNP system

Flaws		Frequency (kHz)	ETSS 96007.1	KHNP System	Ratio/Difference	
4x20% FBH Non-normalized	Volts (P_P)	550	7.43 V	7.69 V	103%	
		150	17.87 V	17.95 V	100%	
4x20% FBH Normalized		550/150 Diff. Mix	4.00 V	4.00 V	0%	
40% FBH Normalized		550/150 Diff. Mix	4.34 V	4.61 V	6%	
60% FBH Normalized		550/150 Diff. Mix	6.46 V	6.78 V	5%	
100% TWH Normalized		550/150 Diff. Mix	7.01 V	7.10 V	1%	
4x20% FBH Normalized		Phases (MxR)	550/150 Diff. Mix	122°	122°	0°
40% FBH Normalized			550/150 Diff. Mix	106°	105°	-1°
60% FBH Normalized	550/150 Diff. Mix		88°	85°	-3°	
100% TWH Normalized	550/150 Diff. Mix		35°	35°	0°	



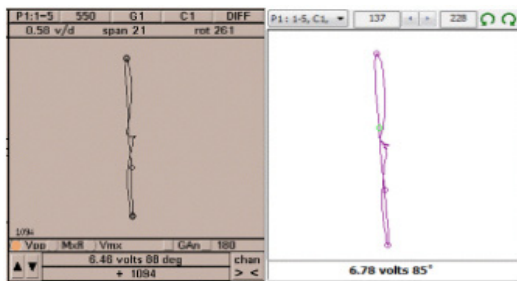
(a) ZETEC (b) KHNP

Fig. 8 Normalized 550/150 kHz bobbin differential signals of 4x20% FBHs



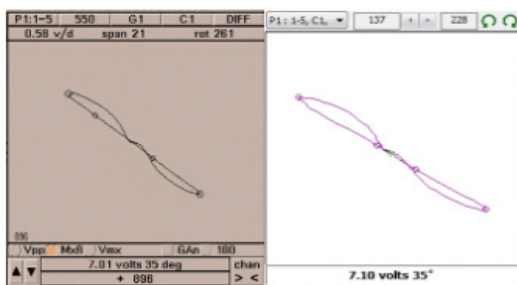
(a) ZETEC (b) KHNP

Fig. 9 Normalized 550/150 kHz bobbin differential signals of 40% FBH



(a) ZETEC (b) KHNP

Fig. 10 Normalized 550/150 kHz bobbin differential signals of 60% FBH



(a) ZETEC (b) KHNP

Fig. 11 Normalized 550/150 kHz bobbin differential signals of 100% TWH

used to remove the tube support signal for facilitating detection of flaws.

As shown in Table 2 and Fig. 6 to Fig. 11, the KHNP system is satisfied with the four requirements for the bobbin probe technique. The amplitude voltage responses of 4x20% TW FBHs for the KHNP system are 103% at 550 kHz and about 100% at 150 kHz of those for the ETSS 96007.1. Differences of all normalized amplitude responses for the KHNP system are within 7% of the qualified technique. The normalized amplitude response of the 100% TWH is almost same as that of the qualified technique. The results also show that the phase angle responses of the FBH and TWH flaws for the KHNP system are within  $\pm 1\%$  of the qualified technique.

### 3.2 Rotating Probe Technique

The ETSS 21410.1 used in the assessment for the rotating probe technique has been applied for the detection of circumferential ODSCC at transition region of tubesheet[4]. Table 3 shows the comparison for the essential variables of the ETSS 21410.1 and the KHNP system. The rotating probe and the EDM notch calibration standard used in the assessment are shown in Fig. 12.

The results of the equivalency assessment for the rotating probe technique are shown in Table 4 and Fig. 13 to Fig. 22. In Table 4, SAI stands for single axial indication and SCI



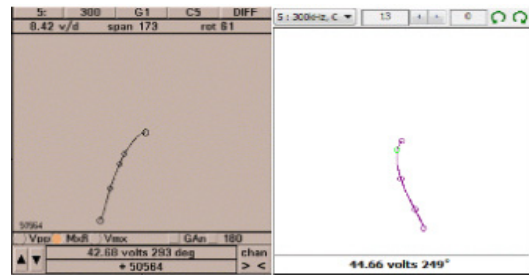
Fig. 12 Rotating probe and EDM-notch calibration standard

denotes single circumferential indication.

As shown in Table 4 and Fig. 13 to Fig. 22, the KHNP system is satisfied with the three requirements for the rotating probe technique. The non-normalized amplitude voltage response from the 100% single axial notch for the KHNP system is 105% of the qualified technique. The ratio of all normalized notch amplitude voltage responses for the KHNP system to the qualified technique for the phase angle responses of the EDM notches are within  $\pm 10\%$ .

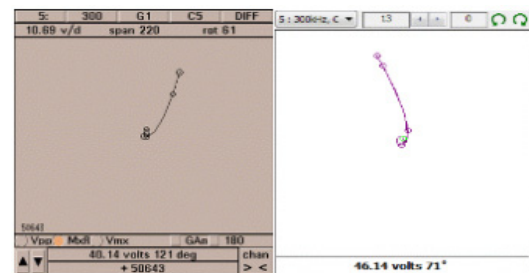
Table 3 Essential variables of the ETSS 21410.1 and the KHNP system

Essential Variables	ETSS 21410.1	KHNP System
Tube Material	I-690	I-690
Tube OD (in)	0.750	0.750
Tube wall (in)	0.043	0.043
Relative current density	32.95@300 kHz	32.95@300 kHz
Probe	Rotating (MRPC™)	Rotating (MRPC™)
Probe type	PP11A	PP11A
Eddy current tester	MIZ-70	KHNP
Acquisition software	ZAC	KHNP-ACQ
Analysis software	Eddynet	KHNP-ANA
Probe manufacturer	ZETEC	ZETEC
Frequency(kHz)	300	300
Volts/Gain	12/0.5	12/0.5
Sample rate	38/25	38/25
Test speed (in/sec)	0.2	0.2
Test direction	Push	Push
Analysis system	HP c3750	PC
Calibration standard	EDM-notch	EDM-notch



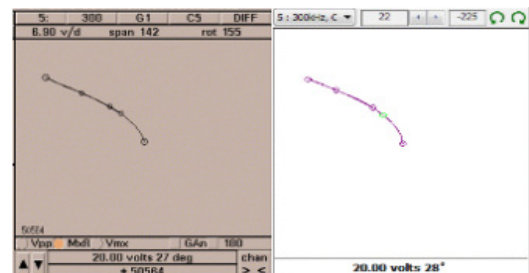
(a) ZETEC (b) KHNP

Fig. 13 Raw 300 kHz +point signals of 100% axial notch



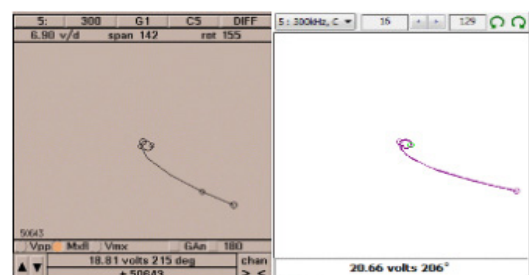
(a) ZETEC (b) KHNP

Fig. 14 Raw 300 kHz +point signals of 100% circumferential notch



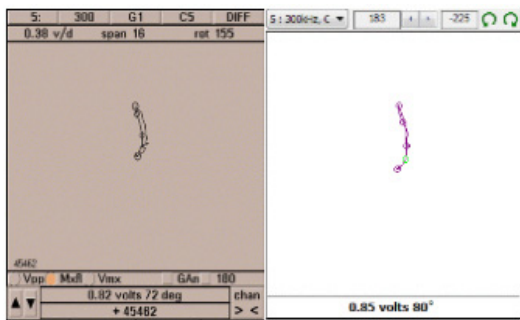
(a) ZETEC (b) KHNP

Fig. 15 Normalized 300 kHz +point signals of 100% axial notch



(a) ZETEC (b) KHNP

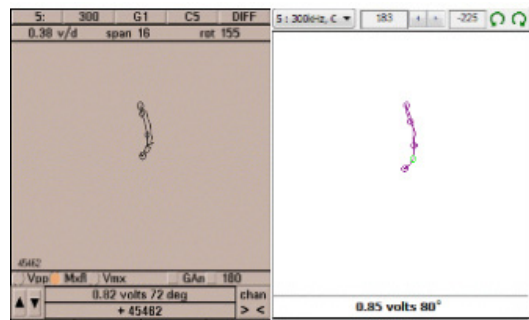
Fig. 16 Normalized 300 kHz +point signals of 100% circumferential notch



(a) ZETEC

(b) KHNP

Fig. 17 Normalized 300 kHz +point signals of 60% OD axial notch



(a) ZETEC

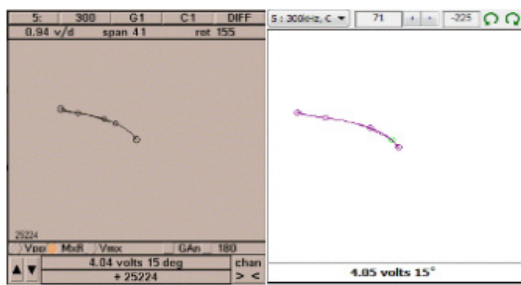
(b) KHNP

Fig. 18 Normalized 300 kHz +point signals of 40% OD axial notch

Table 4 Results of equivalency assessment for rotating probe technique between the ETSS 21410.1 and the KHNP system

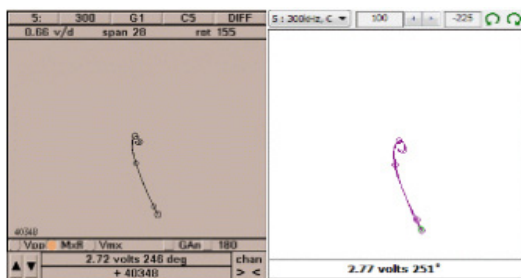
Flaws			ETSS 21410.1	KHNP System	Ratio/Difference
Non-normalized P_P (300 kHz)-Volts					
SAI	TW	100%	42.68 V	44.66 V	105%
SCI	TW	100%	40.14 V	46.14 V	115%
Normalized P_P (300 kHz)-Volts					
SAI	TW	100%	20 V	20 V	0%
SCI	TW	100%	18.81 V	20.66 V	10%
SAI	OD	60%	2.27 V	2.30 V	1%
		40%	0.82 V	0.85 V	4%
SCI	OD	60%	2.72 V	2.77 V	2%
		40%	1.16 V	1.19 V	3%
	ID	40%	4.03 V	4.10 V	2%
Phase MxR (300 kHz)-Degrees					
SAI	TW	100%	27°	28°	1°
SCI	TW	100%	215°	206°	-9°
SAI	OD	60%	64°	70°	6°
		40%	72°	80°	8°
SCI	OD	60%	246°	251°	5°
		40%	257°	262°	5°
	ID	40%	195°	195°	0°





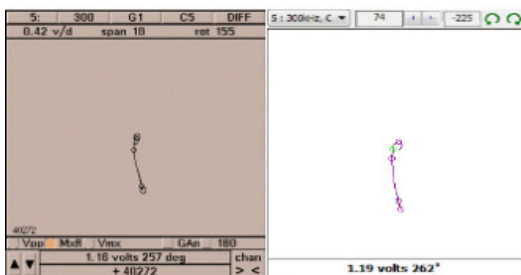
(a) ZETEC (b) KHNP

Fig. 19 Normalized 300 kHz +point signals of 40% ID axial notch



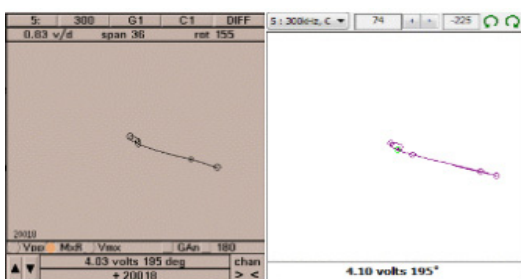
(a) ZETEC (b) KHNP

Fig. 20 Normalized 300 kHz +point signals of 60% OD circumferential notch



(a) ZETEC (b) KHNP

Fig. 21 Normalized 300 kHz +point signals of 40% OD circumferential notch



(a) ZETEC (b) KHNP

Fig. 22 Normalized 300 kHz +point signals of 40% ID circumferential notch

## 4. Conclusions

The KHNP developed an eddy current testing system including eddy current tester and data acquisition-analysis programs. The equivalency assessments for the KHNP system were carried out in accordance with the EPRI examination guidelines [1] and the equivalency project documents [4]. The qualified techniques of the ETSS 96007.1 for the bobbin probe technique and the ETSS 21410.1 for the rotating probe technique were chosen for the assessments in this study, which have been widely used for the inspection of steam generator tubes in the nuclear power plant. The results show that the KHNP system is satisfied with the equivalency requirements within the tolerances of signal amplitudes and the phase angles specified in the EPRI equivalency documents. It is expected that the currently developed KHNP system can be utilized for the field inspection.

## Acknowledgement

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